A White Paper Summarizing a Special Session on Induced Seismicity

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INDUCED SEISMICITY

By Underground Injection

This special technology transfer session for seismologists, regulators, and other stakeholders entitled *"Assessing & Managing Risk of Induced Seismicity by Injection"* was a part of the GWREF Spotlight Series.

The Ground Water Research & Education Foundation (GWREF) is a not-for-profit 501(c) 3 corporation dedicated to promoting research and education related to the protection of ground water.
Our mission is to promote and conduct research, education, and outreach, in the areas of development and application of technical systems, pollution prevention efforts related to ground water protection, underground injection technology, and watershed conservation and protection.

The foundation is comprised of a board made up of volunteers from government, institutes of higher education, and the public appointed through the Ground Water Protection Council.

White Paper Summarizing a Special Session on Induced Seismicity[1]

Chapter 1 - Introduction

The Ground Water Protection Council (GWPC), held its 2013 Underground Injection Control Conference in Sarasota, Florida on January 22-24, 2013. On January 23, the conference included a special session entitled "Assessing & Managing Risk of Induced Seismicity by Underground Injection". The session was presented by the Ground Water Research & Education Foundation (GWREF), a not-for-profit corporation dedicated to promoting research and education related to the protection of ground water. The Foundation is associated with the GWPC.

1.1 The Special Session

The topic of induced seismicity, or earthquakes caused by human activities, has been raised increasingly by the media over the past several years. To help disseminate factual information on the subject, the GWPC and GWREF decided to include a session on induced seismicity in the January underground injection control conference. The session included 12 presentations separated into three groups. Lori Wrotenbery of the Oklahoma Corporation Commission chaired the first group of presentations with a theme of "Studies: Researchers Presenting Findings and Research Strategies". This was followed by a second group of presentations, chaired by Ed Steele of Swift Worldwide Resources, with a theme of "Industry: State of the Art Technology Used to Limit Risk". Wrotenbery presided over a third group of presentations on the theme of "Regulatory".

1.2 The White Paper

This white paper summarizes the information that was discussed during the special session. It is not intended to be a complete and detailed report on the subject, but is generally limited to the information actually presented during the twelve presentations and any associated discussion during the question and answer periods. Note that a detailed technical report on induced seismicity was released by the National Research Council of the National Academy of Sciences (NAS) in 2012. That report contains much broader and in-depth coverage of induced seismicity and was written collaboratively by experts in the field.

[1] The white paper was prepared for GWPC by John Veil of Veil Environmental, LLC.

Since the NAS report was discussed by several speakers, some information relating to cases briefly mentioned by the speakers was expanded by pulling more detailed information from the Council's report. Other information was drawn from the NAS report to provide better documentation for topics discussed by individual speakers. Chapter 3 of this white paper describes the NAS report and its main points.

Some of the material is highly technical and esoteric. That information is very useful to specialists and practitioners. But in order to explain the importance of induced seismicity and the issues surrounding it to a wider audience, this white paper is written in a style and at a level for a broader non-technical audience.

Rather than summarizing each presentation in the order in which speakers actually made their presentations, the white paper pulls material from different presentations into a more thematic narrative that covers the key topics in a coordinated way.

Most of the speakers in the session agreed to let the GWPC post copies of their presentations on the GWPC website. Where those presentations are available, they are directly linked to references in this white paper. For those other presentations whose authors did not authorize the GWPC to post the slides, relevant information is summarized, and reference is made to their names – readers can contact those authors directly for additional information.

The white paper also includes Appendix A, which shows the agenda for the special session.

Chapter 2 –Seismicity

This chapter provides an overview of seismicity by drawing from different presentations.

2.1 What Is Seismicity?

Although several speakers offered their own definitions for induced seismicity, it makes sense to start with the description of seismicity used in the Summary section of the NAS report.

> *"Seismicity induced by human activity related to energy technologies is caused by change in pore pressure and/or change in stress taking place in the presence of (1) faults with specific properties and orientations, and (2) a critical state of stress in the rocks. In general, existing faults and fractures are stable (or are not sliding) under the natural horizontal and vertical stresses acting on subsurface rocks. However, the crustal stress in any given area is perpetually in a state in which any stress change, for example through a change in subsurface pore pressure due to injecting or extracting fluid from a well, may change the stress acting on a nearby fault. This change in stress may result in slip or movement along that fault creating a seismic event. Abrupt or nearly instantaneous slip along a fault releases energy in the form of energy waves ("seismic waves") that travel through the Earth and can be recorded and used to infer characteristics of energy release on the fault."*

That report further states: *"Earthquakes attributable to human activities are called 'induced seismic events' or 'induced earthquakes'*." This second quote includes two relevant points: a) "induced" means attributable to human activities, and b) the terms "seismic events" and "earthquakes" are comparable.

Jeff Bull, an oil and gas industry subject matter expert on induced seismicity, made a presentation on various aspects of induced seismicity. The presentation started with some basic introduction to seismicity – it is useful to include pieces of that introduction here.

Many earthquakes occur every day from natural causes. Most are far too small to be felt by humans at the surface. But seismic instruments can detect and document many of the small events. These frequent small earthquakes do not cause damage to man-made structures.

2.1.1 Magnitude and Intensity of Seismic Events

Seismic events occur with varying degrees of intensity; there are many more small events than larger ones. If an earthquake is strong enough, the energy released during the event may reach the earth surface and cause noticeable shaking. Damage to structures, if any, depends on the amount of energy reaching the surface, the characteristics of the soil, and the structural design and physical condition of the local structures.

The scientific community has developed various scales to characterize the strength of individual earthquakes. The most familiar scale to the public for characterizing the magnitude of earthquakes is the Richter scale, developed in the 1930s. A related scale, developed in the 1970s, that also measures the magnitude of earthquakes is called the Moment Magnitude scale. It is commonly used now by the scientific community, and was used throughout the NAS report. Both scales assign numbers to events of different sizes. The numbers run on a logarithmic scale (i.e., a 4.0 earthquake is ten times larger than a 3.0 earthquake) and represent the amplitude (height) of the seismic waves measured on a seismograph. Bull notes that although the increase in wave amplitude is ten times higher, the amount of energy released may be about 30 times higher.

The Richter scale has no theoretical upper or lower limits. The magnitude of recorded natural events typically ranges from -3 (the lower limit of microseismic sensor sensitivity) to 9+ (the most severe earthquake ever recorded).

Another scale that measures the intensity of earthquakes is called the Modified Mercalli Index (MMI). The MMI uses the perceived effects of a seismic event on the people and structures at the surface to determine its intensity at any given location, but does not provide a single number for any earthquake. The MMI includes 12 levels of seismic event severity, ranging from imperceptible to devastating. The numeric values of the magnitude scales (Richter and Moment Magnitude) as well as the MMI increase with the strength of an event, but do not match up in an exact linear manner. For measuring the impact of an earthquake on people and structures, the MMI level is more useful in describing actual local effects and has been used by the U.S. Geological Survey (USGS) in the development of educational materials for the general public.

The MMI value depends upon many factors including:

- Depth of the seismic event,
- Distance from the seismic event epicenter,
- Geomechanical characteristics, and
- Terrain.

Population density can contribute to reported MMI values because of the likelihood of more reports of shaking and damage when a higher population area experiences an earthquake.

Figure 1 is taken from Bull's presentation – Bull notes on his slide that the table was created by Wikipedia using USGS information. The figure shows the relationship between the Richter scale and the MMI, and describes the types of surface effects that represent events of different magnitude. It also gives an indication of how many earthquakes occur each year within the different MMI ranges.

Figure 1 – Comparison of Richter Magnitude Scale and MMI Values

Richter Magnitude	Description	MMI	Earthquake effect observations	World-wide occurrence
< 2.0	Micro		Micro earthquakes not felt by people and detected by sensitive instruments only.	Continual >8,000 per day
2.0 – 2.9	Minor	1	Imperceptible: Not felt except by a very few people under exceptionally favorable circumstances.	1,300,000 per year (est.)
3.0 – 3.9		2	Scarcely felt: Felt by only a few people at rest in houses or on upper floors buildings.	130,000 per year (est.)
		3	Weak: Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognized as an earthquake.	
4.0 – 4.9	Light	4	Largely observed: Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic. Walls may creak; doors, windows, glassware and crockery rattle.	13,000 per year (est.)
		5	Strong: Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.	
5.0 – 5.9	Moderate	6	Slightly damaging: Felt by all. People and animals alarmed. Many run outside. Walking steadily is difficult. Objects fall from shelves. Pictures fall from walls. Furniture may move on smooth floors. Glassware and crockery break. Slight non-structural damage to buildings may occur.	1,319 per year
		7	Damaging: General alarm. Difficulty experienced in standing. Furniture and appliances shift. Substantial damage to fragile or unsecured objects. A few weak buildings damaged.	
6.0 – 6.9	Strong	8	Heavily damaging: Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.	134 per year
7.0 – 7.9	Major	9	Destructive: Some buildings are damages and many weak buildings are destroyed.	15 per year
8.0 – 8.9	Great	10	Very destructive: Many buildings are damaged and most weak buildings are destroyed.	1 per year
		11	Devastating: Most buildings are damaged and many buildings are destroyed.	
9.0 – 9.9		12	Completely devastating: All buildings are damaged and most buildings are destroyed.	1 per 10 years (est.)
10.0+	Massive	>12	Never recorded, widespread devastation across very large areas.	Unknown

Source: Presentation by Jeff Bull

2.1.2 Location of Seismic Events

Two related terms describe the location at which an earthquake is triggered. The "epicenter" is the location at the surface above the slip event. The "hypocenter" is the event's actual location in the subsurface.

2.2 What Is Induced Seismicity?

Consistent with the NAS report text shown in section 2.1, induced seismicity was defined by several of the speakers as seismic events that are caused by human activities (as opposed to natural geological events). Induced seismic activity has been attributed to a range of human activities including:

- Impoundment of large reservoirs behind dams,
- Controlled explosions related to construction,
- Mine cavity collapse,

- Underground nuclear tests, and
- Energy technologies that involve injection or withdrawal of fluids from the subsurface.

In recent years, many claims have been made that injection related to various forms of energy production have led to increased rates of earthquakes that can be felt by the public. Therefore, the special session focused on the fourth of these categories. Examples of energy technologies include the following, which are discussed in more detail in the next chapter:

- Enhanced geothermal energy,
- Hydraulic fracturing,
- Long-term injection and production associated with enhanced oil recovery (EOR) programs,
- Injection wells used for long-term disposal of produced water and other fluids, and
- Carbon capture and sequestration (CCS) programs.

2.3 What Causes Induced Seismicity?

Many of the speakers emphasized the point that induced seismicity is not caused by the injected fluids lubricating faults. Rather, the induced seismicity is triggered by the increased pore pressure in the rock that effectively reduces the natural friction on a fault. Water is an incompressible fluid such that pressure applied at a wellhead is transmitted to the bottom of the well and out into the formation. This allows the pressure to move over extended distances where it can cause already susceptible faults to slip. The overall physics involved in these processes is very complex; more research is needed to develop a better understanding.

Austin Holland of the Oklahoma Geological Survey (OKGS) reported that most of the Earth's upper crust is near failure. The increased pore pressure from fluid injection effectively reduces friction on faults.

In cases where injection continues over long periods of time, the injected fluids will cause a cumulative rise in formation pressure. An increased formation pressure by itself does not necessarily induce earthquakes, but if faults that are already near failure or susceptible to slippage are located near to the site of increased pressure, an earthquake may be triggered. In order for induced seismicity to take place there needs to be a critically stressed fault near the human activity. Not all faults are equally susceptible – the location, orientation, and properties of the fault play an important role too.

If a particular project involves injecting and removing fluids from the same formation, as in the case of an enhanced oil recovery project, it is the net fluid balance that is important, not just the injected volume.

Robin McGuire of Lettis Consultants International presented factors that affect the potential to generate felt seismic events:

- Rate of injection or extraction,
- Volume and temperature of injected or extracted fluids,
- Pore pressure,
- Permeability of the relevant geologic layers,
- Faults, fault properties, fault location,
- Crustal stress conditions,
- Distance from the injection point, and
- Length of time over which injection and/or withdrawal takes place.

Chapter 3 - National Academy of Sciences Report

Injection of large volumes of fluids into underground formations can increase the potential for seismic events to occur under certain conditions. With the heightened level of U.S. oil and gas production, particularly with the rapid expansion of unconventional oil and gas resources that involve hydraulic fracturing and wastewater disposal through injection wells, Senator Jeff Bingaman of New Mexico, chair of the Senate Energy and Natural Resources Committee, wrote to Department of Energy Secretary Stephen Chu in 2010. Senator Bingaman requested the Secretary to engage the NAS's National Research Council to examine the scale, scope, and consequences of seismicity induced by energy technologies.

The NAS formed a Committee on Induced Seismicity Potential in Energy Technologies. Work began in 2011. A final report was released in June 2012[2].

This white paper does not include all the details of the NAS report. However, the presentation made by Robin McGuire of Lettis Consultants International (a member of the NAS committee that prepared the report) during the special session provides a summary of the report and its findings. Several others speakers made reference to the same report. Therefore, some of the key findings of that report are included here.

3.1 Focus of the NAS Report

According to McGuire's presentation, the NAS report:

- Summarized the current state-of-the-art knowledge on the possible scale, scope and consequences of seismicity induced during the injection of fluids related to energy production,
- Identified gaps in knowledge and the research needed to advance the understanding of induced seismicity, its causes, effects, and associated risks,
- Identified gaps and deficiencies in current hazard assessment methodologies for induced seismicity and research needed to close those gaps, and
- Identified and assessed options for interim steps toward best practices, pending resolution of key outstanding research questions.

[2] National Academy of Sciences, 2012, "Induced Seismicity Potential in Energy Technologies," prepared by an NAS Committee on Induced Seismicity Potential in Energy Technologies, published by the National Academies Press, Washington, DC, 300 pp. The report can be ordered in hard copy or downloaded in .pdf format at http://www.nap.edu/catalog.php?record_id=13355.

The report focused its attention on induced seismicity specifically associated with four energy technologies:

- Geothermal energy,
- Oil and gas production,
- Wastewater disposal in injection wells, and
- Carbon capture and storage (CCS).

Each of these is discussed in the following sections. The descriptions given below represent the level of detail provided in McGuire's presentation. The full NAS report contains far more detail and examples than are described here. Readers are encouraged to examine the report for additional information.

3.2 Geothermal Energy

Geothermal energy can be produced in at least three different ways. Some formations contain hot steam in the pores and fractures of the rock. These are called "vapor-dominated" systems. A well-known example of this type of production is the Geysers field located 75 miles north of San Francisco.

Others contain hot liquid water in the pores and fractures of the rock, and are referred to as "liquid–dominated" systems. Both of these systems require some water injection to maintain pressure and heated working fluids.

The third type of geothermal system is known as "enhanced geothermal systems (EGS)" or as "hot dry rock". In those formations, the hot formation does not contain abundant natural water or steam. To take advantage of the high temperature of the rock, extensive hydraulic fracturing must be done to promote water introduction into the rock and circulation of water within the rock formation. In addition, a water source must be injected into the rock as a heat-transfer fluid.

Geothermal systems employ both injection and withdrawal of water. Operators attempt to keep a balance between fluid volumes produced and the fluids replaced by injection to maintain reservoir pressure. Unlike the other forms of energy reviewed in the NAS report, geothermal energy has very high temperatures in the underground formation. The temperature difference between formation and injected water introduces an additional driving force for rock disturbance from thermal impacts.

3.2.1 Geothermal Influences on Induced Seismicity

The NAS report concludes that induced seismicity in geothermal systems appears related to both net fluid balance considerations and temperature changes produced in the subsurface. Different forms of geothermal resource development appear to have differing potential for producing felt seismic events:

- High-pressure hydraulic fracturing undertaken in some geothermal projects (EGS) has caused seismic events that are large enough to be felt.
- Temperature changes associated with geothermal development of hydrothermal resources has also induced felt seismicity (The Geysers).

3.3 Oil and Gas Production

Several aspects of the oil and gas production cycle involve injection and/or withdrawal of large volumes of fluids from underground formations. The NAS report focused on three of these. The first is oil and gas extraction. Typically this removes large volumes of fluids over decades. Operators attempt to balance the volume of fluids injected with the volume extracted as the fields mature. The relevant examples provided in the NAS report are all related to production from conventional oil and gas formations; most such cases are decades old.

The second aspect is enhanced recovery, in which fluids are injected to extract remaining oil and gas and maintain reservoir pressure. Often as fields grow more mature and the natural reservoir pressure diminishes, it is necessary to begin injection of fluids. The most common form is secondary recovery (injection of water for water flooding). When secondary recovery has reached its practical or economic limits, tertiary recovery (enhanced oil recovery using steam, CO_2, polymers, and other materials) may be employed. The key is maintaining pressure balance within the formation.

The third aspect is hydraulic fracturing. Although hydraulic fracturing has been performed on more than 1 million wells since the mid-1940s, the technique has become a household term in the past five years, as shale gas development has flourished in the United States. Hydraulic fracturing of horizontal shale gas wells often uses 5 million gallons of water injected under pressures high enough to fracture the shale rock.

3.3.1 Oil and Gas Extraction Influences on Induced Seismicity

Generally, oil and gas extraction from conventional wells has not caused significant seismic events. However, withdrawal of oil or gas from the subsurface can result in a net decrease in pore pressure in the reservoir over time, particularly if fluids are not reinjected to maintain or regain original pore pressure conditions.

There have been a limited number of earthquakes associated with oil and gas production. About half of these cases are from the United States. Two other well-documented cases were found in France and Uzbekistan.

3.3.2 Oil and Gas Enhanced Recovery Influences on Induced Seismicity

Intuitively, processes that withdraw fluids from a formation and reinject fluids back into the same formation are less likely to cause large increases in pore pressure. Enhanced recovery operations were found by the NAS committee to have minimal influence of induced seismicity. McGuire reported that relative to the large number of waterflood projects for secondary recovery, the small number of documented instances of felt induced seismicity suggests that those projects pose small risk for events that would be of concern to the public.

The committee did not identify any documented, felt induced seismic events associated with EOR (tertiary recovery). They concluded that the potential for induced seismicity is low.

3.3.3 Oil and Gas Hydraulic Fracturing Influences on Induced Seismicity

Although the rate of injection of fluids for hydraulic fracturing is quite high, the duration of a typical frac job is relatively short – typically just a few days, with any given frac stage subjected to elevated pressures for only a few hours.

McGuire reports that the committee concluded that the process of hydraulic fracturing a shale gas well does not pose a high risk for inducing felt seismic events. They estimated that about 35,000 wells had been hydraulically fractured for shale gas development to date in the United States. Among all those frac jobs, only a few cases of felt induced seismicity from hydraulic fracturing for shale gas had been documented worldwide (examples from Oklahoma, the Horn River basin in Canada, and the United Kingdom).

3.4 Produced Water Disposal Wells

The Underground Injection Control (UIC) program regulates injection wells. The U.S. Environmental Protection Agency (EPA) and states that have received authority to administer the UIC program have permitted more than 150,000 injection wells for managing produced water from oil and gas operations. Many of these wells are used for injecting fluids for secondary or tertiary recovery as described in section 3.3. But an estimated 30,000 wells are used for disposal of wastewater to formations that do not produce oil and gas.

3.4.1 Produced Water Disposal Well Influences on Induced Seismicity

Typically these disposal wells inject moderate volumes of fluids on a regular basis for many years. Given their ongoing injection and high cumulative volume, they may be thought to have some potential for inducing seismicity, if the local faults are susceptible. However, McGuire reports that the NAS committee found very few felt induced seismic events reported as either caused by or likely related to these wells.

A large percentage of disposal wells operate for years without creating any felt seismic events. But a small percentage of disposal wells do seem to be associated with clusters of earthquakes, typically small to moderate in strength. High injection volumes may increase pore pressure, and in proximity to existing faults could lead to an induced seismic event. Several examples of earthquake clusters linked to injection well activity are described in the next chapter.

Earthquakes associated with disposal wells are not necessarily limited in time and space to injection operations. The area of potential influence from injection wells may extend over several square miles, with earthquakes triggered more than 10 miles away. Induced seismicity may continue for months to years after injection ceases in some special cases, but the mechanisms that cause such effects are not well understood.

Evaluating the potential for induced seismicity in the location and design of injection wells is difficult because there are no cost-effective ways to locate faults and measure in situ stress. In a later chapter, several state regulators describe ways in which their agencies are trying to avoid locating new disposal wells in areas that are susceptible to induced seismicity.

3.5 CCS Operations

Over the past decade and a half, extensive research has been conducted on capturing CO_2 from large exhaust gas sources like power plants or gas processing plants. Once the CO_2 is captured, it can be converted to a supercritical state and injected into an underground formation for permanent storage or sequestration. The volumes of CO_2 that would ultimately need to be sequestered to have a meaningful impact of atmospheric CO_2 levels will be extremely large. To the extent that full-scale CCS projects are implemented, they could represent very significant fluid injection programs.

3.5.1 CCS Influences on Induced Seismicity

According to McGuire's presentation, the only long-term (~14 years) commercial CO_2 sequestration project in the world is located at the Sleipner field offshore from Norway. That project injects CO_2 captured from an oil and gas production platform. The program is done at a small scale relative to the commercial projects proposed in the United States. Extensive seismic monitoring has not indicated any significant induced seismicity.

There is no experience with the proposed injection volumes of liquid CO_2 in large-scale sequestration projects (> 1 million metric tonnes per year). If the reservoirs behave in a similar manner to oil and gas fields, these large volumes have the potential to increase the pore pressure over large areas and may have the potential to cause significant seismic events.

One other consideration is that CO_2 has the potential to react with the host/adjacent rock and cause mineral precipitation or dissolution. The effects of these reactions on potential seismic events are not understood.

3.6 Comparative Impacts

McGuire's presentation included several charts taken from page 96 of the NAS report that show a side-by-side comparison of different energy activities and the amount of fluids injected on a daily and annual basis. That report is subject to copyright; therefore the figures are not reproduced here. The point of those charts is that some activities may have high daily injection volumes but have a short duration (e.g., hydraulic fracturing). When compared over an annual cycle, they have lower cumulative injection volumes than activities like CCS that have lower daily injection rates but continue throughout the entire year.

The charts also point out that some activities involve a relatively close balance of injection and withdrawal volumes (e.g., enhanced recovery) while CCS or disposal wells are presumed to incorporate injection only. Thus their cumulative impacts on pore pressure are likely to be more pronounced.

McGuire also showed a table that was adapted from Table S1 on page 6 of the NAS report. The table summarizes information for each of the energy activities regarding the number and strength of felt seismic events per year. The most prominent source of felt seismic events is vapor-dominated geothermal production at the Geysers, with an estimate 300-400 felt earthquakes per year since 2005. However, only one of those events had a magnitude greater than 4.0. The NAS report notes that the operators at the Geysers meet regularly with representatives of local communities, county government, federal and state regulatory agencies, the USGS, and national laboratory scientists in order to discuss the field operations and the recently observed seismicity.

Out of 30,000 water disposal wells surveyed, only 8 felt seismic events have been noted. However, 7 of those 8 events had a magnitude greater than 4.0.

3.7 Government Involvement and Coordination

McGuire noted that mechanisms are lacking for efficient coordination of government agency response to induced seismic events. He explained that responsibility for oversight of activities that can cause induced seismicity is dispersed among a number of federal and state agencies. Recently, potential induced seismic events in the United States have been addressed in a variety of manners involving local, state, and federal agencies, and research institutions. These agencies and research institutions may not have resources to address unexpected events; further, more events could stress this ad hoc system.

While EPA has overall regulatory responsibility for fluid injection under the Safe Drinking Water Act, and most states have delegated regulatory authority for the UIC program, neither the Code of Federal Regulations nor state regulations directly address induced seismicity. The USGS has the capability and expertise to address monitoring and research associated with induced seismic events. However, their mission does not focus on induced events. Significant new resources would be required if their mission is expanded to include comprehensive monitoring and research on induced seismicity.

Typically state agencies do not have the resources to undertake detailed seismic investigations. However, Tom Tomastik of the ODNR reported that his agency has undertaken its own seismic monitoring program. The agency hired two new geologists in 2012 to work in the UIC program (one of the new employees has a PhD in seismology).

Additionally, the ODNR began seismic monitoring for microseismic events around a few of the new Class II injection well sites. The ODNR purchased nine portable seismographs with the capability of measuring movements in all three directional axes. Three of the new seismographs were deployed around a new disposal well. The ODNR is installing portable seismic units around some of the new Class II injection wells and will start monitoring prior to commencement of injection operations and will continue to monitor for a period of time after injection operations commence. They will continue to monitor for microseismic events up to approximately six months after initiation of injection operations. If no evidence of larger seismic events, the portable seismic stations will be moved to another new disposal well location.

This type of evaluation requires extensive resources and a great deal of time. Ohio's program is commendable, but may not be practical in other states. Chapter 6 discusses several approaches to evaluating risk on a case-by-case basis.

Chapter 4 – Examples of Induced Seismicity

Many of the presenters described examples of specific cases in which injection activities caused detectable earthquake activity. Some were mentioned quickly as examples, while others were described in greater detail. This chapter provides summaries of some of those cases. The examples are organized by the four energy sectors used in the previous chapter.

4.1 Induced Seismicity from Geothermal Energy Production

4.1.1 Basel, Switzerland

Robin McGuire made brief reference to a magnitude 3.4 earthquake associated with injection of water for an enhanced geothermal project in the center of Basel, Switzerland in 2006. He did not offer any details. The NAS report provides a more detailed description of the case. During the hydraulic fracturing process for the system, many small seismic events were detected with several higher than magnitude 3.0. This caused the developers to discontinue the stimulation efforts and ultimately to abandon the project.

4.1.2 The Geysers

Robin McGuire made a few references to the Geysers geothermal project in California. A summary table in his presentation reported that there had been 300-400 felt seismic events per year since 2005. Between 1 and 3 of these had magnitude greater than 4.0. The NAS report offers much more information on the frequency and magnitude of the events.

4.2 Induced Seismicity from Oil and Gas Extraction

None of the presenters described examples in which extraction of oil and gas directly contributed to seismic events through removal of fluid leading to reduction of pore pressure in underground formations. However, the NAS report did provide two examples. These are the Lacq gas field in southwestern France and the Gazli gas field in Uzbekistan. Since these were not discussed in the special session, they are not mentioned further here. But interested readers can find more information in the NAS report.

4.3 Induced Seismicity from Enhanced Recovery Operations in Oil and Gas Fields

4.3.1 Rangely, Colorado

Stuart Ellsworth of the Colorado Oil and Gas Conservation Commission (COGCC) provided some background on the Rangely field in northwestern Colorado. Oil production started many decades ago and was later augmented by water flooding operations beginning in 1957. Within a few years, the formation pore pressure rose to a level that triggered seismic events up to a magnitude 3.4. The area of injection was experiencing about 50 minor earthquakes per day.

The oil company operating the field agreed to let the USGS conduct an experiment to determine whether they could turn earthquakes off and on by injecting or withdrawing water from the formation. The researchers were successful in this experiment. When the injection ceased, the earthquakes dropped from more than 50 to fewer than 10 per day. When they began injection again, the daily number jumped back up to over 50. Over a two-year period, the USGS turned earthquake activity off, on, off, on, and off again.

Austin Holland of the OKGS included a figure from a 1976 scientific paper that shows how the number of earthquakes tracked the amount of water injected or withdrawn. The NAS report includes much more detail on the experiment.

4.3.2 Other Cases

A summary table in McGuire's presentation reported that there had been felt seismic events at 18 water flooding sites around the world. Three of these had magnitude greater than 4.0. The NAS report offers more information on the frequency and magnitude of the events.

4.4 Induced Seismicity from Hydraulic Fracturing of Oil and Gas Wells

Holland provided specific case examples from wells in Oklahoma for which he believed that hydraulic fracturing had possibly contributed to seismic events. He also mentioned other examples from the United Kingdom and Horn River basin in British Columbia, Canada.

The NAS report notes that the very low number of earthquakes relative to the large number of hydraulically fractured wells is likely due to the short duration of injection of fluids and the limited fluid volumes used in a small spatial area.

4.4.1 Oklahoma

Holland suggested that a small percentage of the hydraulically fractured wells in Oklahoma may have induced seismic events. He cited the fracturing in Eola Field in Garvin County as possibly contributing to about 100 earthquakes, with magnitudes as high as 2.9. He also suggested that fracturing activities in the Union City Field in Canadian County may have contributed to about 10 small earthquakes. However, these conclusions will require additional verification.

4.4.2 Blackpool, UK

Several of the presenters mentioned this case as a prominent example of earthquakes associated with hydraulic fracturing. However, none of the presenters provided details. The NAS report contains more detailed description. Cuadrilla Resources began drilling and completing some of the first shale gas wells in the UK in 2011. The hydraulic fracturing triggered earthquakes of 2.3 and 1.5 magnitude. The 2.3 earthquake was felt widely by residents, which created a great deal of media attention. Cuadrilla suspended drilling and fracturing while it undertook an extensive study.

4.5 Induced Seismicity from Produced Water Disposal Wells

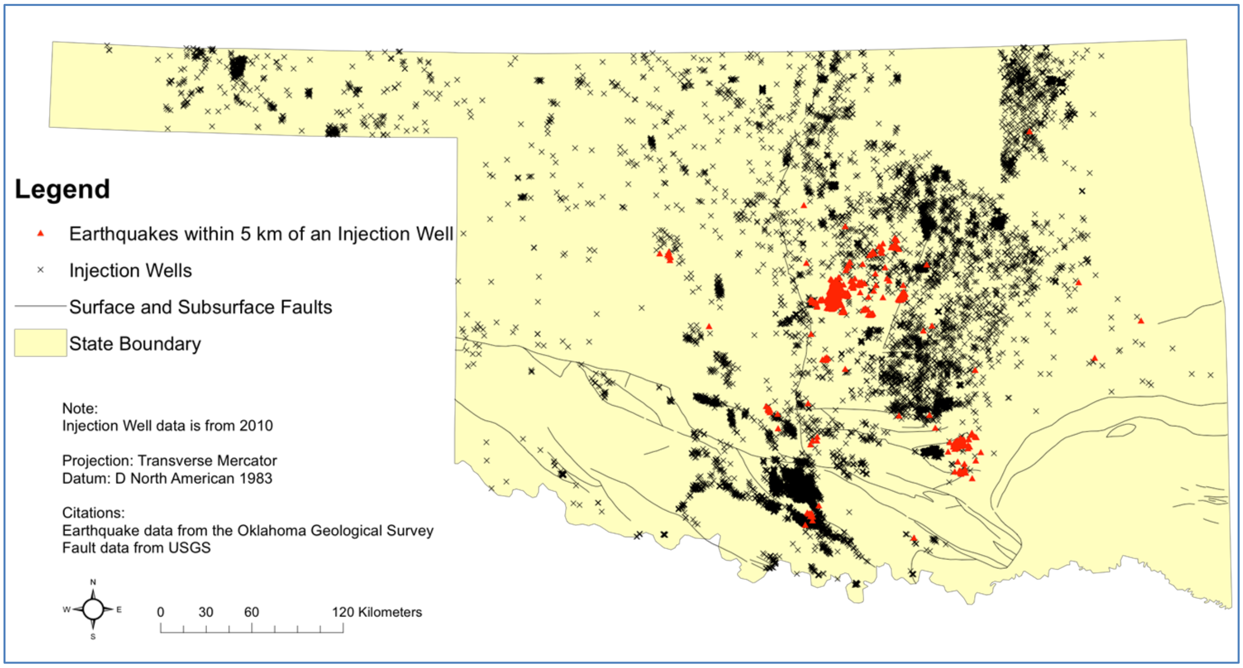
Compared to the other types of energy projects, disposal wells are more commonly linked to induced seismic events. This section describes examples relating to injection of oil and gas produced water. Two other examples of wells injecting other types of fluids are provided in section 4.6.

4.5.1 Oklahoma

Austin Holland reported on the relationship between earthquakes and injection wells in Oklahoma. Figure 2 plots the location of both of those categories on a map. Although some of the injection wells are located within 5 km of the earthquakes, there are many other injection wells throughout the state that clearly have not triggered earthquakes.

Holland described two cases in which injection of produced water into disposal wells was a potential cause for earthquakes. The first is an earthquake swarm of about 1,800 earthquakes located around Jones, OK, not far from Oklahoma City. The maximum magnitude of the events was 4.0 while the majority of them were of much smaller magnitude. Several large volume injection wells are located within 8-12 miles of the earthquake swarm. Prior to injection operations, the number of earthquakes in the area was small. Earthquake recurrence statistics

Figure 2 – Location of Injection Wells, Faults, and Earthquakes in Oklahoma in 2010



Source: Presentation by Austin Holland

in that area are not similar to those observed for the rest of Oklahoma. The data show a larger variation of active fault-plane orientations than expected. As a result, interpretation of the data is not as simple as anticipated. The Oklahoma Geological Survey continues to review the data and hopes to learn if the earthquake swarm was influenced by the disposal wells.

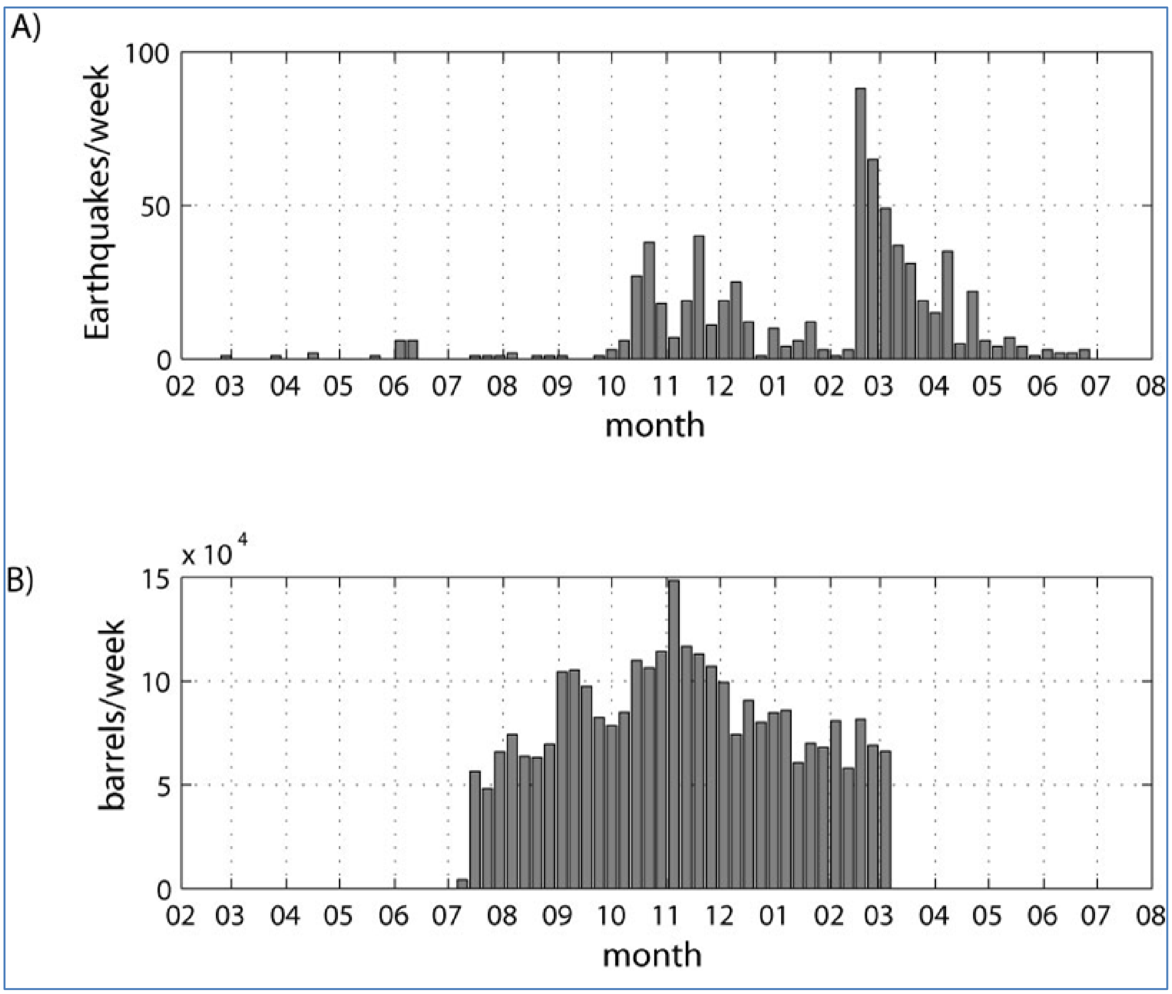
The second example described by Holland is a magnitude 5.7 earthquake near Prague, OK in November 2011. He noted that there are three UIC disposal wells within a mile of the earthquake location. Holland reported that other authors (in a manuscript currently under review for the journal Geology) propose the earthquakes were induced from injection from the 3 wells. Their hypothesis is based in part on the fact that the main shock occurred on a splay of the Wilzetta fault, which is consistent to be active in the regional stress-field. They also noted that the earthquakes have the characteristics typical of a natural aftershock sequence. Holland noted that as in the Jones swarm case, it is possible that these earthquakes were triggered by injection, but not certain. Where both natural and induced seismic events occur in the same area it can be very difficult to distinguish them from one another.

4.5.2 Arkansas

Scott Ausbrooks of the Arkansas Geological Survey reported on a cluster of earthquakes that occurred in the central portion of the state in the vicinity of several disposal wells. Following injection of produced water and flowback water from shale gas production into several wells, a previously unknown fault, the Guy-Greenbrier fault, was illuminated by over 1,300 earthquakes with magnitudes up to 4.7 that occurred starting in September 2010. However, the vast majority of these events were relatively small in magnitude.

Figure 3, taken from Ausbrooks' presentation, shows the relationship between the number of earthquakes in that region and the volume of water injected. The data show a strong correlation between cumulative volume of water injected and the number of earthquakes, but as displayed in the bottom chart, there is a lag time of several months between the commencement of injection and the uptick in earthquakes. A similar relationship can be seen after injection is stopped – the earthquakes continue for another few months.

Figure 3 – Relationship between Volume of Water Injected and Number of Earthquakes



Source: Presentation by Scott Ausbrooks; the co-author is Stephen Horton of CERI.

Ausbrooks reported that the Guy-Greenbrier fault was already critically stressed prior to the start of injection. The earthquakes along the Guy-Greenbrier fault began after the start of injection at well #1 with intense seismic activity following the start of injection at well #5. The injection of fluids increased pore pressure in the Ozark aquifer. Because of the hydraulic connection between the Ozark aquifer and the Guy-Greenbrier fault, pore pressure could also have increased in the fault zone.

Ausbrooks concluded that given the spatial and temporal correlation between the disposal wells and activity on the fault, it would be an extraordinary coincidence if the earthquakes were not triggered by fluid injection. As discussed below in section 6.3, the AOGC placed a permanent moratorium on permitting any new or additional Class II disposal wells in a large area surrounding the Guy-Greenbrier and Enola seismically active areas.

4.5.3 Ohio

Tom Tomastik of the ODNR described the series of earthquakes that occurred near Youngstown, OH. The Northstar #1 injection well is located in an industrial district in Youngstown in the northeastern portion of the state. The lower portion of the well was originally drilled as a stratigraphic test well to 9,184 feet in April 2010. The DNR issued a permit to convert the wells to a Class II injection well in July 2010. Injection commenced on December 22, 2010.

The first two seismic events happened on March 17, 2011. Ten additional events followed through the end of 2011. Figure 4 shows the seismic events and their magnitudes.

Figure 4 – Seismic Events in Youngstown, OH

DATE	ORIG. TIME UTC	EPICENTER	MAGNITUDE	FELT
Mar. 17, 2011	10:42:20.22	41.11, -80.70	2.1	Not Felt
Mar. 17, 2011	10:53:09.51	41.11, -80.68	2.6	Felt (27 reports)
Aug. 22, 2011	08:00:31.50	41.12, -80.73	2.2	Not Felt
Aug. 25, 2011	19:44:20.99	41.10, -80.71	2.4	Not Felt
Sept. 02, 2011	21:03:26.20	41.12, -80.69	2.2	Felt (few)
Sept. 26, 2011	01:06:09.82	41.11, -80.69	2.6	Felt
Sept. 30, 2011	00:52:37.58	41.11, -80.69	2.7	Felt (300 reports)
Oct. 20, 2011	22:41:09.54	41.11, -80.68	2.3	Not Felt
Nov. 25, 2011	06:47:26.58	41.10, -80.69	2.2	Not Felt
Dec. 24, 2011	06:24:57.98	41.119, -80.694	2.7	Felt (90 reports)
Dec. 31, 2011	20:04:59.03	41.118, -80.693	4.0	Felt (more than 4,000)
Jan. 13, 2012	22:29:33.45	41.11, -80.69	2.1	Not Felt

Source: Presentation by Tom Tomastik

After the September seismic events, downhole testing was performed on the Northstar #1 injection well. In October, a tracer survey was conducted and indicated that injection fluids were entering 26 multiple injection zones from 8,215 to 8,940 feet. On December 30th, at the request of the Director of ODNR, the well operator shut down the Northstar #1 well. As described in some of the previous examples, often the seismic events continue after the injection has ceased. On the following day, the largest event to date occurred, with a magnitude of 4.0. In response, the Governor placed an indefinite moratorium on the other three drilled Northstar injection wells and one outstanding Northstar injection permit within a seven mile radius around the Northstar #1 injection well.

Tomastik reported that studies done by Lamont-Doherty Earth Observatory on the seismic data indicate there may be an unknown fault within the Precambrian rocks near the Northstar #1 injection well. Injection from the Northstar #1 well may have communicated with this potential fault and caused the seismic activity. Data continues to be collected and evaluated.

4.5.4 West Virginia

Tom Bass of the West Virginia Department of Environmental Protection (WVDEP) reported on multiple seismic events in central West Virginia during 2010 near a disposal well. West Virginia has 52 active non-commercial and 14 active commercial UIC disposal wells. These wells are important for the disposal of fluids associated with oil and natural gas development, particularly from the Marcellus Shale.

A commercial UIC well located in Braxton County, WV began experiencing small earthquakes in the range of magnitude 2.2 to 3.4 in April 2010. The same area had experienced one seismic event of 2.5 magnitude in 2000 prior to the injection well being drilled.

The well was originally drilled for production but was not economical. Therefore the operator elected to convert it to a disposal well. The well passed a mechanical integrity test making sure casing, tubing, and packer were tight prior to injection. All reports submitted by the operator prior to the earthquakes indicated that the well operated within permitted pressure limits. In response to the seismic activity, the Office of Oil and Gas placed a limit on the volume that could be injected within a 30 day period (15,000 bbl). No conclusive evidence was linked between the disposal well and the seismic activity.

4.5.5 Texas

McGuire briefly mentioned a series of earthquakes that occurred near the Dallas-Ft. Worth airport during 2008-2009. The proposed cause was injection of produced water from shale gas operations into a disposal well. He provided no details.

Adel Younan of ExxonMobil briefly mentioned another example in the same section of Texas. Although he provided no details, a speaker at a previous GWPC conference (Cliff Frohlich of the University of Texas) had described a series of earthquakes near Cleburne, Texas to the southwest of Fort Worth. Frohlich's investigation suggested that the earthquakes had been caused by a disposal well nearby.

4.6 Induced Seismicity from Other Types of Disposal Wells

Several presenters mentioned two well-known cases of disposal wells injecting fluids other than produced water that contributed to induced earthquakes. Both of these examples are found in Colorado.

4.6.1 Rocky Mountain Arsenal

Stuart Ellsworth of the COGCC provided some background on injection activities at the Rocky Mountain Arsenal near Denver. In the late 1950s, liquid waste was stored in ponds at the U.S. Army's Rocky Mountain Arsenal. The Army decided to inject the liquid into a 12,045-foot deep well drilled into deep, pre-Cambrian crystalline rock.

Injection began in March 1962. Less than a year after injection began, earthquakes began occurring in the vicinity. Thousands of small earthquakes were recorded near the Arsenal. In 1967, two earthquakes occurred with magnitude of 5.0. In 1968 injection stopped, and the Army began removing fluid from the Arsenal well at a very slow rate in an effort to reduce earthquake activity.

Ellsworth noted several features of this example that contributed to the observed earthquakes. These same factors also apply to the next example – Paradox Valley.

- Large injection volumes,
- High injection rate, and
- Low porosity and low permeability reservoir.

Holland included a figure from a 1968 scientific paper that shows the strong correlation between the volume of waste injected at the Rocky Mountain Arsenal and the earthquake frequency.

4.6.2 Paradox Valley

Hal Macartney of Pioneer Resources presented a detailed review of injection at Paradox Valley in southwestern Colorado. Although he gave the presentation, the listed authors of the presentation are Lisa Block and Chris Wood of the U.S. Department of Interior – Bureau of Reclamation. Macartney's presentation is not included on the GWPC website. Additional information relating to this project is taken from the presentation by Stuart Ellsworth and from the NAS report.

The Bureau of Reclamation operates the Colorado River Basin Salinity Control Project in the Paradox Valley to reduce the amount of salt entering the Dolores River and ultimately the Colorado River. They collect naturally occurring seepage of salt brine before it can contaminate the Dolores River. The intercepted salty water is disposed of by a combination of evaporation ponds and injection to a deep limestone formation at a depth of approximately 14,100 to 15,750 feet. The Bureau's scientists expected that this process might trigger earthquakes and thus deployed a network of local seismometers to monitor any activity.

During 6 years of pre-injection seismic measurement, the Bureau recorded only one earthquake. However, once injection began in July 1996, earthquakes were recorded almost immediately. Minor earthquakes continued through mid-1999, and two magnitude 3.5 events occurred in June and July of 1999. In response to the higher magnitude earthquakes, the Bureau of Reclamation initiated a program to cease injection for 20 days every six months. After experiencing a magnitude 4.3 earthquake in May 2000, they reduced injection to every other month. The result has been no more earthquakes over magnitude 4.0.

After monitoring injection into the Paradox Valley Unit injection well for almost 15 years, the Bureau of Reclamation has recorded over 4,600 induced seismic events. The largest seismic event occurred on May 27, 2000 and had a magnitude of 4.3. Macartney reports that about 1.92 billion gallons have been injected to date.

Macartney concluded that injection has induced earthquakes up to 16 km from the injection well, including on the far side of Paradox Valley. Decreasing the injection flow rate reduced the rate of induced seismicity and caused a region around the well to become aseismic. However, it did not prevent the occurrence of felt earthquakes, nor did it stop the geographical expansion of the induced seismicity.

The largest induced earthquakes with magnitudes of 3.0 and above occur in a narrow band about 2 km from the well, on the side away from the salt valley. The occurrence of larger-magnitude earthquakes appears to correlate with high long-term average injection pressures. The response time of the seismicity to injection is increasing.

Chapter 5 – Evaluating the Risk of Induced Seismicity

There are numerous injection wells and production wells in the United States. Hydraulic fracturing is conducted on thousands of wells each year. If felt seismicity were induced equally by all of those activities, there would be thousands of reports of earthquakes in many states each week. Yet the relatively small number of felt earthquakes associated with energy production activities suggests that not all individual injection activities pose the same degree of risk. This chapter discusses some of the factors that relate to the risk and severity of induced seismicity and describes two separate risk evaluation systems developed by the oil and gas industry. It also describes risk models developed under DOE's research programs.

5.1 NAS Report Recommendations on Assessing Risks of Induced Seismicity

Robin McGuire summarized the finding made by the NAS committee regarding assessment of risks. The committee believes that methods do not exist currently to evaluate the hazards posed by individual projects. The types of information and data required to provide a robust hazard assessment include:

- Net pore pressures,
- In situ stresses,
- information on faults,
- Background seismicity, and
- Gross statistics of induced seismicity and fluid injection for the proposed site activity.

The committee recommended that a detailed methodology should be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The methodology would involve making assessments before operations begin in areas with a known history of felt seismicity, then following up with subsequent assessments in response to any observed induced seismicity.

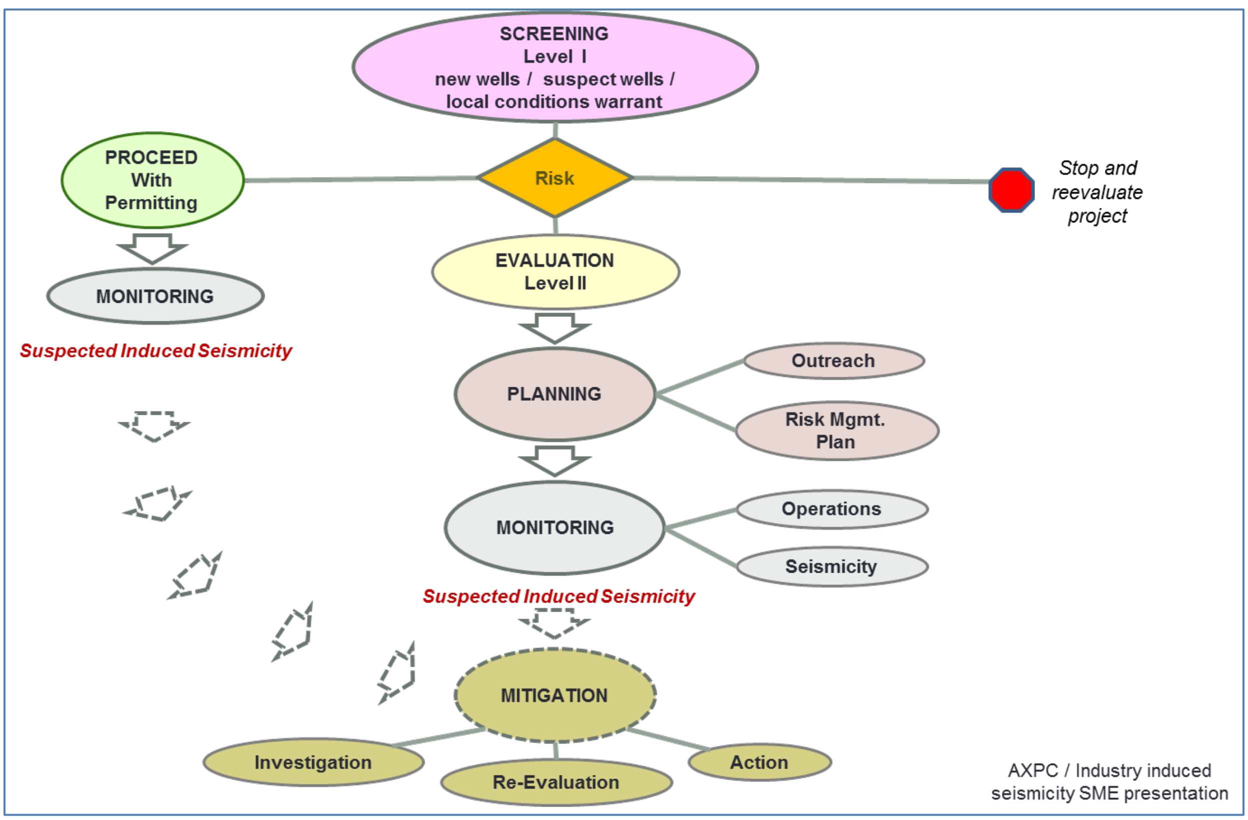
This type of effort was recently begun in Ohio. Tom Tomastik reported on the ODNR's new seismic evaluation program. Some of the new Class II injection wells are being selected for pre-injection seismic monitoring based upon the geology and the proximity of the injection zone in relation to the Precambrian basement rocks, where most of the seismic activity occurs in Ohio. Monitoring would continue for six months after injection begins. If no significant induced seismicity is detected, the monitors will be moved to another location.

McGuire reported that the NAS committee further recommends that data related to fluid injection (e.g., well locations, injection depths, injection volumes and pressures, time frames) should be collected by state and federal regulatory authorities in a common format and made accessible to the public (through a coordinating body such as the USGS). In addition, in areas of high-density of structures and population, regulatory agencies should consider requiring that data on fault identification for hazard and risk analysis be collected and analyzed before energy operations are initiated.

5.2 Risk Management Protocol Proposed by Industry Subject Matter Experts

Jeff Bull , an oil and gas industry subject matter expert on induced seismicity, shared a framework for screening, evaluation, planning, monitoring, and mitigation focused on wastewater injection wells. The framework was proposed by members of an industry working group representing companies from the American Exploration and Production Council and other industry participants. Bull noted that the framework is intended to be a "fit for purpose framework to manage the risk of induced seismicity and that it is scalable, allowing the operator to define the potential risk/impact at hand and then 'right size' any evaluation by selecting the appropriate tools to perform the evaluation". A flowchart of the framework is shown in Figure 5.

Figure 5 – Framework for Evaluating Risks of Induced Seismicity



Source: Presentation by Jeff Bull

Readers are referred to Bull's presentation for all the details. Some of the main points are summarized below. The first level of screening looks at new wells, any existing wells suspected of induced seismicity, and at other places where local conditions warrant. Depending on the evaluation, three possible outcomes can be reached:

- Proceed with permitting,
- Stop and reevaluate the project, or
- Proceed to additional evaluation.

If additional evaluation is the chosen outcome, the next step involves assessing the possibility of seismic events and ground motion occurring as a result of fluid disposal and estimating the impact on local population, property, or environment, including distress, damage, or loss. Some of the items that would be reviewed include:

- Key geologic horizons and features,
- Regional stress assessment,
- Surface features,
- Ground conditions,
- Ground response,
- Local seismic events,
- Reservoir characterization,
- Reservoir properties, and
- Disposal conditions.

The next step involves planning and communication/outreach. Figure 6 shows the "traffic light" planning protocol for assessing risks.

Figure 6 is a hypothetical example that includes ratings of six factors (the blue rows). The actual threshold values of a traffic light system would be based on specific local conditions. Depending on the ratings given for each factor at a particular location, the project is assigned to a green, amber, or red category that helps to determine the next steps.

If a project receives a green rating, it could move ahead. At this point a variety of monitoring would be implemented. Some of the monitoring would measure the injected fluid itself while other monitoring would focus on the reservoir and any local or regional seismic activity that is observed. If the project receives an amber or red rating, risk mitigation would be considered and implemented as appropriate before continuing activities.

Figure 6 – Risk Assessment Plan Using Traffic Lights

Green — Continue operations – no seismicity felt at surface (MMI I-II)*

Amber — Modify operations – seismicity felt at surface (MMI II-III+)*

Red — Suspend operations – seismicity felt at surface with distress and/or damage (MMI V+)*

Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	none	none	none	Very Light	Light	Moderate	Moderate Heavy	Heavy	Very Heavy
Peak Acceleration (%g)	<0.17	0.17 to 1.4	1.4 to 3.9	3.9 to 9.2	9.2 to 18	18 to 34	34 to 65	65 to 124	>124
Peak Velocity (cm/s)	<0.1	0.1 to 1.1	1.1 to 3.4	3.4 to 8.1	8.1 to 16	13 to 31	31 to 60	60 to 116	>116
Magnitude	1 – 2.9	3 – 3.9	4 – 4.4	4.5 – 4.9	5 – 5.4	5.5 – 5.9	6 – 6.4	6.5 – 6.9	7.0+
Modified Mercalli	I	II to III	IV	V	VI	VII	VIII	IX	X+

Traffic Lights *

Source: Presentation by Jeff Bull

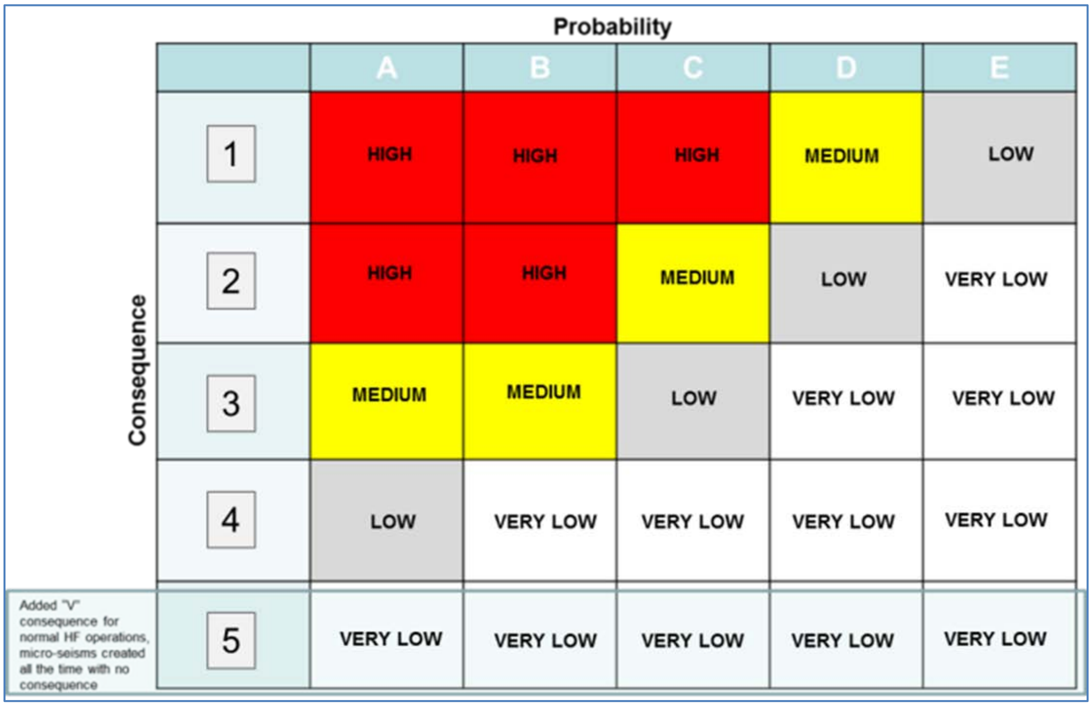
5.3 Risk Management Framework Proposed by ExxonMobil

Adel Younan of ExxonMobil described a possible risk management framework based on various technical considerations that were developed by a multi-disciplinary in-house team. This approach uses a "Risk Matrix" to assess risk level by a qualitative assessment of potential probabilities and consequences of an induced seismic event. After the risk level is identified, possible risk mitigation approaches can be evaluated (effectiveness/cost) and considered for implementation based on local conditions. The approach considers four levels of risk, with the following assigned categories:

- White – very low risk → continue operations
- Grey – very low risk → continue operation
- Yellow – medium risk → adjust operations; consider steps to mitigate risk
- Red – high risk →consider suspending operations; mitigate to reduce risk

The ExxonMobil protocol uses a matrix with probability on one axis and consequences on the other axis. Figure 7 shows the matrix. On the probability axis, A is highly likely, and E is very highly unlikely. On the consequence axis, 1 is MMI > VIII, and 5 is MMI of I to IV. The presentation includes details on the criteria that are used to rank the project.

Figure 7 – Risk Matrix Approach for Assessing Potential Induced Seismicity in Wastewater Disposal Wells and Hydraulically Fractured Wells

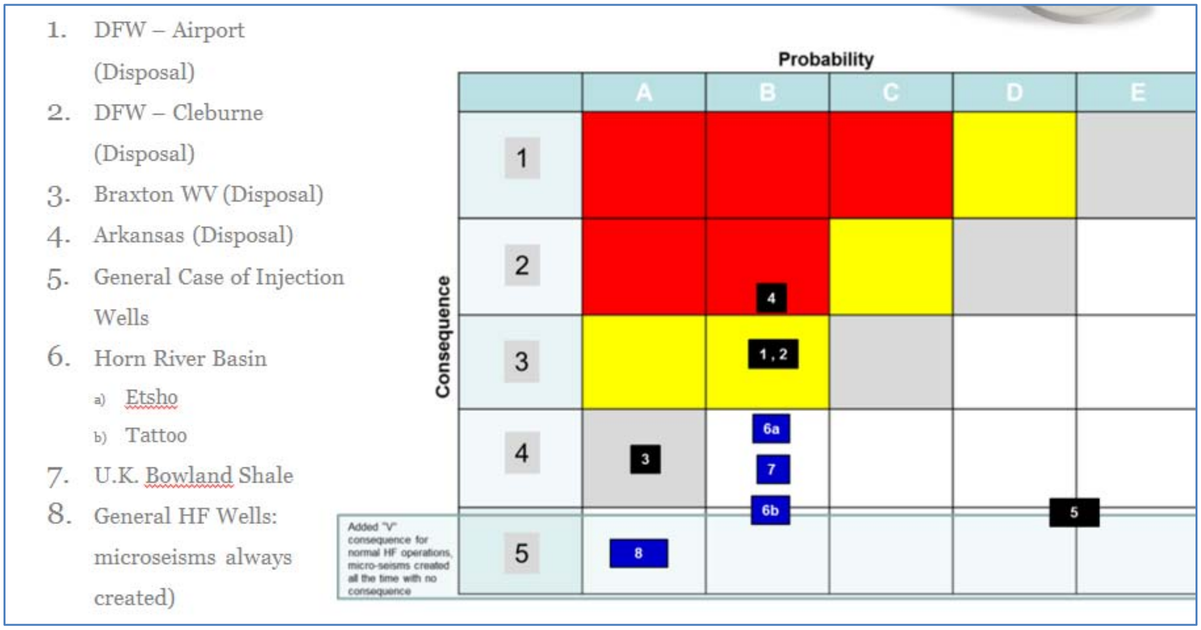


Source: Presentation by Adel Younan

To illustrate how the risk assessment methodology could be applied, Younan gave examples using four specific injection wells and two specific cases of hydraulic fracturing, as well as the general examples of normal injection well operations and hydraulic fracturing operations (where microseisms are routinely created as part of the stimulation process).

Figure 8 shows these examples plotted on the induced seismicity risk matrix. For example, two disposal wells in Texas that were linked to induced seismicity (Dallas/Fort Worth airport and Cleburn) were placed in box B3. The Braxton disposal well in West Virginia was placed in box A4. The Arkansas disposal wells were placed in box B2. Younan rated injection wells in general as falling at the intersection of rows 4 and 5 and columns D and E (i.e., very low consequence and probability of occurrence). He rated three specific hydraulic fracturing projects (two Canadian projects and the Blackpool site in the United Kingdom) in box B4. He indicated that hydraulic fracturing in general always creates microseisms but that the risk would fall into box A5 (i.e., high probability, but low consequence).

Figure 8 – Application of Risk Assessment to Example Wells



Source: Presentation by Adel Younan

Younan concluded that approaches to assess and manage seismicity risk should:

- Be encouraged,
- Be based on sound science,
- Take into account the local conditions, operational scope, geological setting, historical baseline seismicity levels, and
- Reflect reasonable and prudent consideration of engineering standards and codes related to seismicity structural health.

Seismicity monitoring and mitigation should be considered in local areas where induced seismicity is of significant risk. In such areas, appropriate monitoring and mitigation should include:

- A mechanism to alert the operator quickly to the occurrence of seismicity significantly above local historical baseline levels, and
- A procedure to modify and/or suspend operations if seismicity levels increase above threshold values for maintaining local structural health integrity and minimizing secondary damage.

Younan also emphasized that any specific methods and/or approaches selected for monitoring and mitigation should be fit for purpose and based on local conditions and the risk level, working collaboratively.

5.4 DOE Risk Models Relevant to Induced Seismicity

Grant Bromhal of DOE's National Energy Technology Laboratory reported on some of the DOE research efforts currently underway that deal with induced seismicity. DOE's National Risk Assessment Partnership (NRAP), with a team that includes 5 national labs (Lawrence Berkeley National Lab, Lawrence Livermore National Lab, Los Alamos National Lab, National Energy Technology Laboratory, and Pacific Northwest National Lab), is focused around quantifying risks associated with carbon storage in underground formations. One such area is the potential for induced seismic events resulting from large-scale CCS projects. Additionally, DOE and other federal agencies have research programs targeting induced seismicity around other energy-related areas such as geothermal resources, unconventional oil and gas recovery, and wastewater disposal.

NRAP has developed an Integrated Assessment Model with three components:

- RSQSim1—simulates tectonic earthquakes and slow slip events on faults, adapted to use time-dependent pore pressure changes,
- EMPSYN—calculates ground accelerations and velocities, and
- SIMRISK—calculates a frequency-magnitude distribution.

Bromhal reported that Generation 1 of the IAM for Probabilistic Seismic Hazards Assessment of single faults was released in July 2012. DOE expects that Generation 2 will be available in the spring of 2013. It will incorporate multiple faults and time periods, a calculation of the nuisance risk, and the ability to included parameter sensitivity. DOE plans a Generation 3 version of the IAM. It will incorporate higher frequencies in ground motion, full risk, and ties to fault leakage risk.

Regarding cooperation between federal agencies, Bromhal noted that DOE, USGS, and EPA have had a recent discussion on unconventional resource research. They included induced seismicity as an area for future collaboration. DOE and USGS have ongoing efforts in natural and induced seismic hazards analysis. The agencies proposed holding annual collaborative meetings between agencies and with other players to assess gaps/needs.

Chapter 6 – Regulatory Considerations

The final portion of the special session included remarks from EPA and several states describing the efforts that had been made to establish regulations relating to induced seismicity.

6.1 EPA

Keara Moore of EPA's Office of Ground Water and Drinking Water spoke in the special session but did not use any presentation slides. She stated that the subject of induced seismicity does concern EPA, particularly if the seismicity creates conditions that would harm any underground source of drinking water (USDW). At this time, EPA has no national rulemaking directly focused on induced seismicity under development. However, EPA's UIC National Technical Workgroup, with representatives from the regional EPA UIC program offices, is developing a report on the subject. The report would not carry the weight of regulations but could help to explain EPA's perspective on the subject. Moore reported that a draft of the workgroup's report is now being reviewed.

6.2 Ohio

Tom Tomastik of the ODNR made two presentations in the special session. His presentation on the Northstar #1 well and the seismic events associated with it was covered in Chapter 4. In this section, Tomastik's other presentation that reviewed Ohio's response to the Northstar #1 incident and the state's subsequent rulemaking is discussed.

The Northstar #1 well was closed in December 2011. The ODNR immediately made changes to its Class II saltwater injection well program. Three other Class II wells nearby were shut down. The ODNR put a hold on the issuance of any new permits.

The ODNR initiated drafting of new regulations to help prevent larger magnitude induced seismicity associated with Class II injection in late spring of 2012. By July of that year, the Governor issued Executive Order 2012-09K as an emergency amendment of UIC Rules 1501:9-3-06 and 1501:9-3-07 of the Ohio Administrative Code. This Executive Order allowed for the implementation of new draft UIC rules into the legislative process.

The new UIC Class II saltwater injection well rules proceeded through the legislative process, were passed and went into effect in October 2012. The ODNR started to issue new Class II saltwater injection well permits again in November 2012. The new permits incorporated the requirements from the new regulations. The chief of the division issuing the permits could include various new monitoring on a case-by-case basis:

- Pressure fall-off testing,
- Geological investigation of potential faulting within the immediate vicinity of the proposed injection,
- Submittal of a seismic monitoring plan,
- Testing and recording of original bottomhole injection interval pressure,
- Minimum geophysical logging suite, such as gamma ray, compensated density-neutron, and resistivity logs,
- Radioactive tracer or spinner survey, and
- Any such other tests the chief deems necessary.

In addition the new permits would not allow drilling and completion of the wells into the Precambrian basement rock. No injection would be allowed until the results of the monitoring are evaluated. Upon review of the data, the chief can withhold injection authority, require plugging of the well, or allow injection to commence. The chief has the authority to implement a graduated maximum allowable injection pressure. All new Class II injection wells must continuously monitor the injection and annulus pressures to maintain mechanical integrity. They must include a shut-off device installed on the injection pump set to the maximum allowable injection pressure.

To supplement the new permitting requirements, the ODNR established a new state seismic monitoring program. This was described previously in section 3.7.

6.3 Colorado

Stuart Ellsworth of the COGCC described the ways in which Colorado evaluates injection projects in relation to their potential for induced seismicity. The COGCC's permit process considers:

- Injection volume,
- Pressure below the fracture gradient, and,
- Input from the Colorado Division of Water Resources and Colorado Geological Survey to reduce the potential for induced seismicity related to UIC Class II wells.

The COGCC permit writer calculates a maximum injection volume, based on thickness and porosity from geophysical logging data. By COGCC policy, the injection volume is restricted to a one-quarter mile radial volume and the height of the injection formation.

COGCC's policy is to keep injection pressures below the fracture gradient, which is defined uniquely for each injection well, minimizing the potential for seismic events related to fluid injection. Some injection wells do not need to inject under pressure because the formation will take water on a vacuum. Maximum surface injection pressure is calculated based on a default fracture pressure gradient of 0.6 psi per foot of depth or other data provided by the applicant.

Beginning in September 2011, the COGCC UIC permit review process was expanded to include a review for seismicity potential by the Colorado Geological Survey. If historical seismicity has been identified in the vicinity of a proposed Class II UIC well, COGCC requires an operator to define the seismicity potential and the proximity to faults through geologic and geophysical data prior to any permit approval.

6.3 Arkansas

Scott Ausbrooks of the Arkansas Geological Survey described the earthquake swarm around the Guy-Greenbrier fault beginning in 2010. He did not discuss the regulatory changes introduced by the Arkansas Oil and Gas Commission (AOGC) following those seismic events. But the NAS report did include some information on those regulations.

In January 2011, the AOGC placed a permanent moratorium on permitting any new or additional Class II disposal in a 1,150-square-mile area surrounding the Guy-Greenbrier and Enola seismically active areas. Operators with existing Class II wells were required to report daily injection pressures and volumes to the AOGC Director. In the surrounding Fayetteville Shale development area, the AOGC Director may propose additional requirements for any new disposal wells.

6.4 West Virginia

During his presentation, Tom Bass mentioned that the West Virginia Department of Environmental Protection had no plans to develop regulations specifically focused on induced seismicity. He did note that injection permits would be issued on a case-by-case basis.

Chapter 7 - Review of Major Issues and Findings

This chapter lists a few of the major issues and findings discussed during the special session.

1. Natural seismic events (earthquakes) occur regularly in many locations, but most of them are very small in magnitude and are not felt by humans at the surface, nor do they cause damage to surface structures. The Richter scale measures the size of the wave on a seismograph, whereas the Modified Mercalli Index measures the extent of impact occurring at the surface to people and structures.

2. Many of the seismic events are naturally occurring, but some can be caused by human activities. These are referred to as "induced seismicity".

3. The special session and this white paper focus on induced seismicity resulting from energy activities, including geothermal production, oil and gas extraction, enhanced recovery, and hydraulic fracturing, disposal wells used to inject produced water or other wastewaters, and carbon capture and storage projects. The information presented over several hours and summarized here served to enlighten a wider audience and provide some factual information concerning the risks associated with activities that can cause induced seismicity. The NAS report provides a greater body of historical information on this subject and is referenced frequently throughout the white paper.

4. In general, the hazards posed by geothermal operations are not significant because project operators both inject and withdraw water from the formations, thereby keeping the formation pore pressures from climbing dramatically, although constant minor tremors are often associated with such activities. In one noteworthy enhanced geothermal project located at Basel, Switzerland, a large water injection effort to open pathways in the hot rock caused felt earthquakes of sufficient concern to residents in that city that the project was subsequently cancelled.

5. Induced seismicity may occur occasionally in association with oil and gas extraction, but the number of documented cases is extremely small.

6. Induced seismicity rarely occurs during enhanced recovery operations. During such operations, fluids are injected into a formation while oil and gas are withdrawn from the same formation, thereby keeping formation pore pressures from rising dramatically.

7. Hydraulic fracturing involves injection of fluids at high rate for a short period of time. In nearly all cases, the potential for felt seismicity is very low, although a few cases have been observed where unique conditions were present. However, these have not led to any significant surface damage. The NAS report concluded that hydraulic fracturing does not pose a high risk for induced seismicity.

8. Tens of thousands of disposal wells are employed each day to inject produced water and other wastewaters into formations that are not hydrocarbon bearing. Most of these pose low risk of induced seismicity, but given the ongoing injection and cumulative formation pressure build up over time, there is some potential that disposal wells can contribute to induced seismicity. Most wells are completed in areas and geological formations that are not likely to lead to induced seismicity, but several well-documented examples are described in this white paper where seismic activity was linked to disposal wells (e.g., Ohio, Arkansas, Oklahoma, and Texas). These are typically due to some geological anomalies or faults in those locations.

9. The relatively new concept of large-scale injection of CO_2 into underground formations as part of carbon capture and storage projects could lead to induced seismicity. The ongoing, long-term injection of CO_2 could lead to increased formation pore pressure.

10. The oil and gas industry is aware of the potential for its activities to induce seismic events in certain circumstances. Two different frameworks for assessing the risk for individual injection projects were described during the special session.

11. Most state regulatory agencies do not have regulations that focus specifically on induced seismicity. The white paper describes some regulatory initiatives put into play in Colorado, Ohio, and Arkansas. EPA does not have regulations specifically focused on induced seismicity, but its UIC National Technical Workgroup is currently developing a position paper on the subject.

Appendix A – Agenda for Special Session

Assessing & Managing Risk of Induced Seismicity by Underground Injection: A Special session for seismologists, regulators, and other stakeholders

January 23, 2013

Moderator: Lori Wrotenbery, Oklahoma Corporation Commission
Part 1 - Studies: Researchers presenting findings and research strategies

- Abstract 22: Potential for Induced Seismicity within Oklahoma - **Austin Holland**, OK Geological Survey
- Abstract 23: Preliminary Report on the Northstar #1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area – **Tom Tomastik**, Ohio DNR
- Abstract 7: Induced Seismicity Potential and Energy Technologies - **Robin McGuire**, Lettis Consultants International, Inc.
- Abstract 19: Disposal of Hydraulic Fracturing Flowback Fluid by Injection into Subsurface Aquifers Triggers Guy-Greenbrier Earthquake Swarm in Central Arkansas - **Scott Ausbrooks**, Arkansas Geological Survey
- Abstract 29: Research in the Area of Induced Seismicity – **Grant Bromhal**, USDOE-NETL

Moderator: Edward Steele, Swift Worldwide Resources
Part 2 - Industry: State of the art technology used to limit risk

- Abstract 35: Induced Seismicity and the Oil and Gas Industry Oil and Gas Industry – **Jeff Bull**, oil and gas industry subject matter expert on induced seismicity
- Lessons Learned at Paradox Valley - **Hal Macartney**, Pioneer Resources
- Abstract 27: Technical Elements to Consider in a Risk Management Framework for Induced Seismicity - **Adel Younan**, ExxonMobil Upstream Research Company

Moderator: Lori Wrotenbery, Oklahoma Corporation Commission
Part 3 - Regulatory

- Abstract 36: EPA Overview - **Keara Moore**, EPA Office of Ground Water & Drinking Water
- Abstract 24: Ohio's New Class II Regulations and Its Proactive Approach to Seismic Monitoring and Induced Seismicity – **Tom Tomastik**, Ohio DNR
- Abstract 28: **Tom Bass,** West Virginia DEP, Office of Oil & Gas
- Abstract 30: **Stuart Ellsworth**, Colorado Oil & Gas Conservation Commission

Induced Seismicity Session Wrap up discussion

Potential for induced seismicity within Oklahoma

Austin Holland
Oklahoma Geological Survey
University of Oklahoma

Outline

- Induced Seismicity Background
- Earthquakes and Injection Regional Context
- Identified cases of possibly induced seismicity in Oklahoma
  - cases from hydraulic fracturing up to 2% of wells completed
- Potential cases of induced seismicity within Oklahoma
- Difficulties in identifying induced seismicity from UIC Class II wells

Earthquake Triggering

Natural Causes

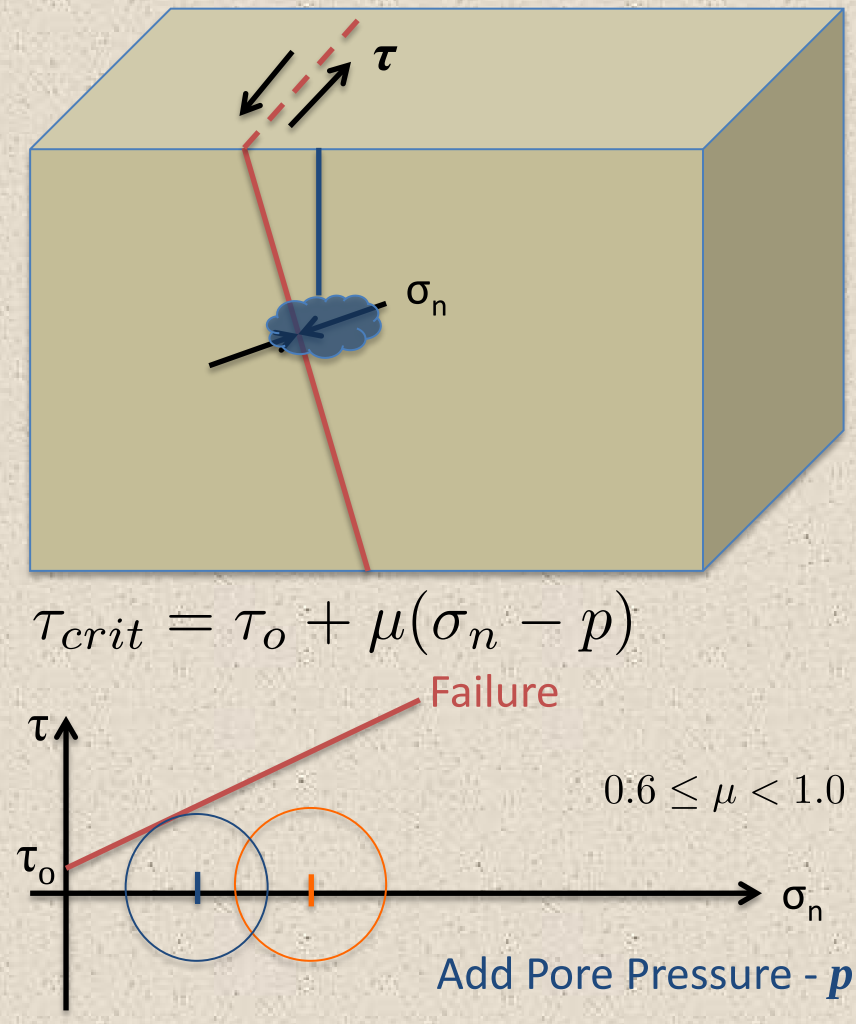
- Dynamically by the passage of seismic waves
  - typically from very large earthquakes distances > 1000 miles
- Statically by local stress changes from previous earthquakes
  - Small amounts of stress changes have been shown to trigger earthquakes
  - as little as 2-7 psi
- Natural fluid movement
  - May be the cause of many aftershocks of large earthquakes
- Hydrologic loads

Anthropogenic

- Reservoir Impoundment
- Mining and Oil Production (Mass Removal)
- Fluid Injection
- Geothermal Production & Thermal Contraction

Induced Seismicity from Fluid Injection

- Most of the Earth's upper crust is near failure
- Increased pore pressure from fluid injection effectively reduces friction on fault
  - or in Mohr-Coulomb space, moves the circle towards failure



Pressure Diffuses Within the Earth

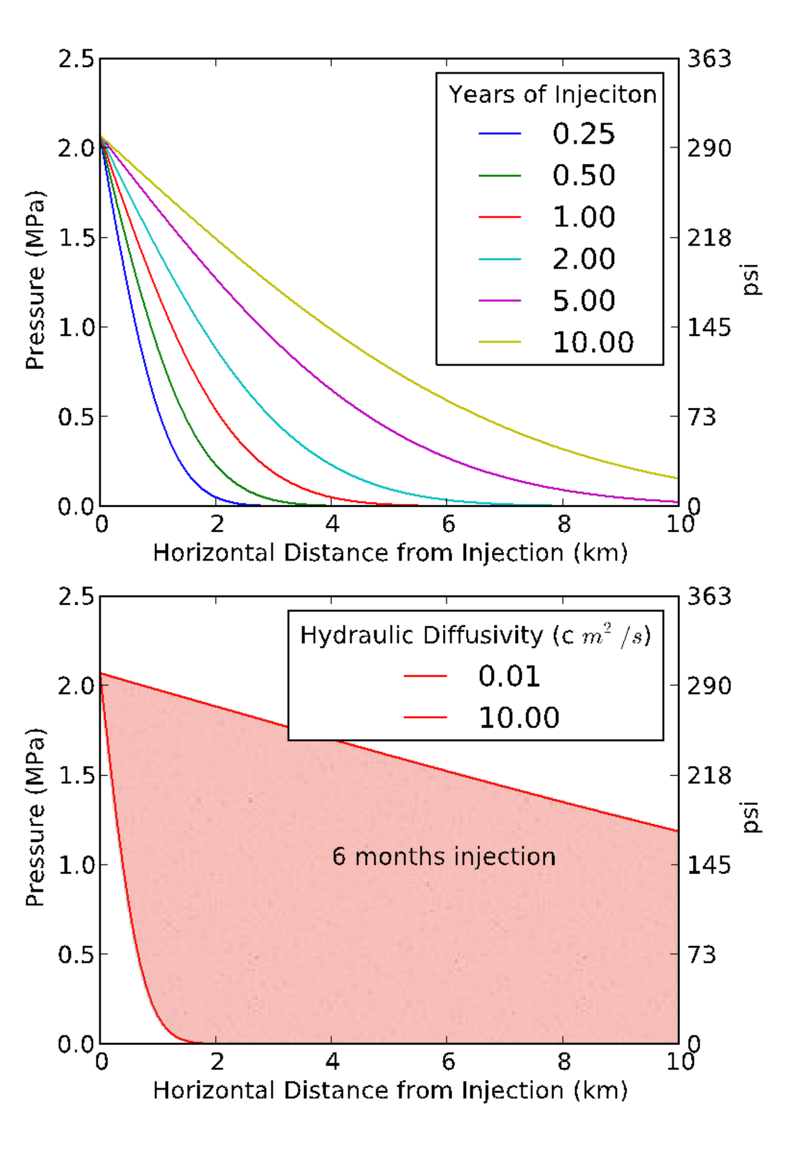
- Pressure increase is not due to actual fluid flow
  - Can be much more rapid
  - Because water is fairly incompressible it is similar to an elastic response although slower
  - Diffusivity constant is

$$c = T/S$$

T = transmissivity

S = storativity

- Pressure increases over time



Talwani et al. (2007) J. Geophys Res.

Risk from Injection Induced Earthquakes

- Hydraulic Fracturing (Lower Risk)
  - Magnitudes generally less than 0
  - Observed maximum magnitude (M_{max}) 3.1-3.4
  - Injection duration may be weeks
- Water Disposal (Higher Risk)
  - Observed M_{max} 5.3-5.7
  - Damage from some events
  - Injection duration may be decades

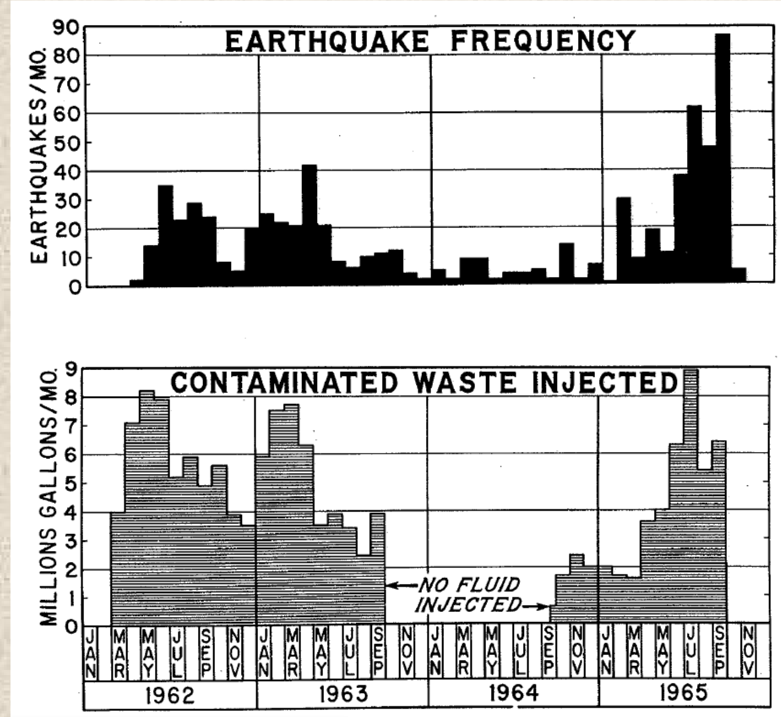
Injection Induced Seismicity

Best Documented Cases

- Rangely, CO – Raleigh et al. (1976) Science
- Paradox Valley, CO, Ake et al. (2005) Bull. Seismol. Soc. Amer.
- KTB, Germany, Baisch et al. (2002) Bull. Seismol. Soc. Amer.
- Basel, Switzerland, Deichmann & Giardini (2009) Seismol. Res. Letters
- Rocky Mountain Arsenal, CO, Hsieh & Bredehoeft (1981) J. Geophys. Res.

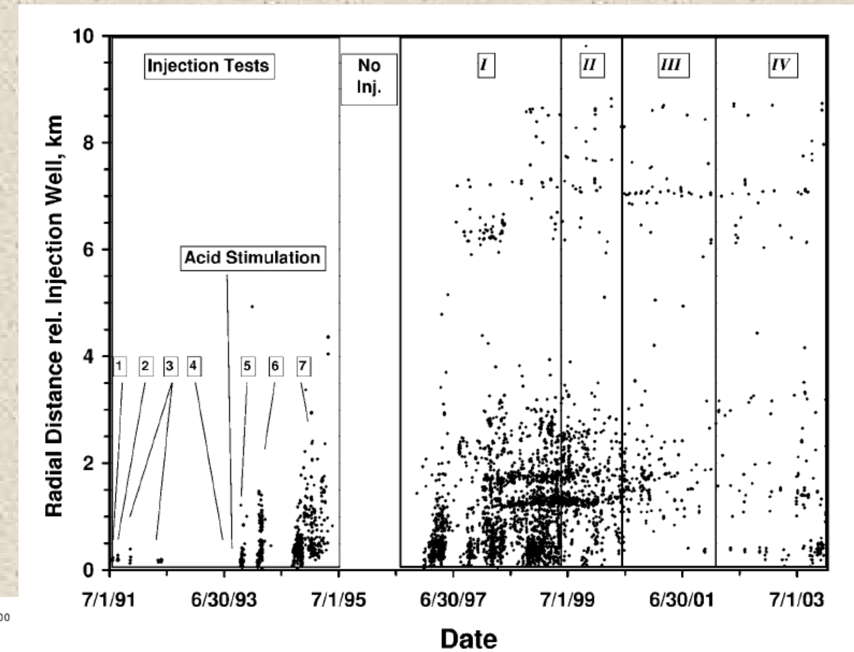
General Observations

- Earthquakes generally occur first near the well and migrate away from the well with time
- Earthquakes have a clear temporal correlation to injection
- Time and spatial distribution of earthquakes can generally be related to diffusion of pore pressure
- Earthquakes can occur over long distances >20 km
- Modifying injection parameters alters earthquake production



RMA, Healy et al. (1968)

Paradox Valley, Ake et al. (2005)



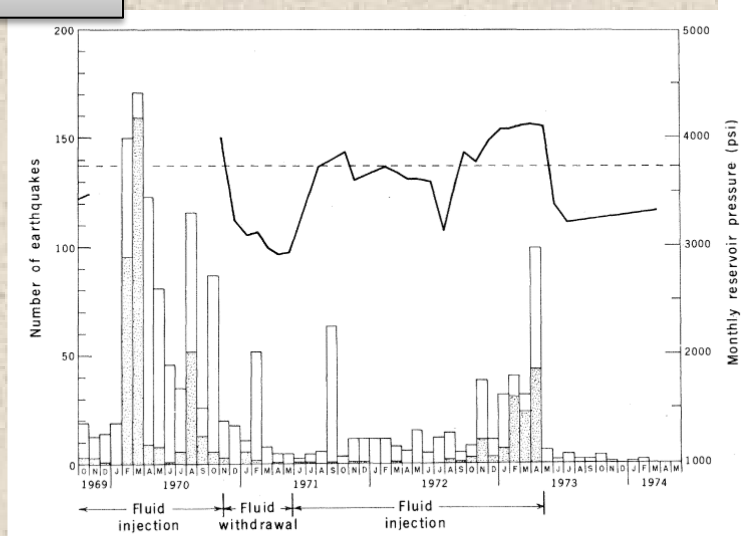
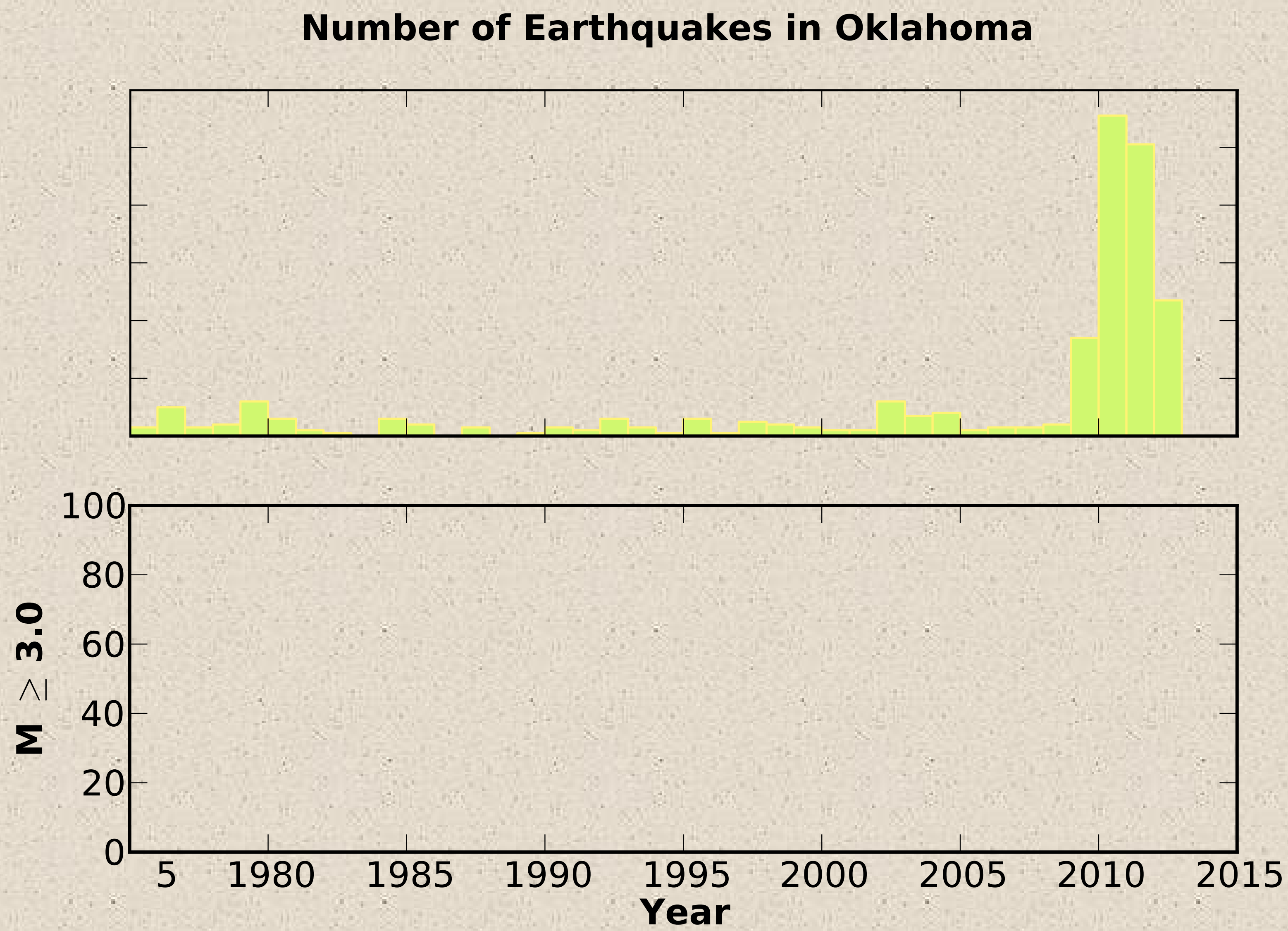


Fig. 7. Frequency of earthquakes at Rangely. Stippled bars indicate earthquakes within 1 km of experimental wells. The clear areas indicate all others. Pressure history in well Fee 69 is shown by the heavy line; predicted critical pressure is shown by the dashed line.

Rangely, Raleigh et al. (1976)

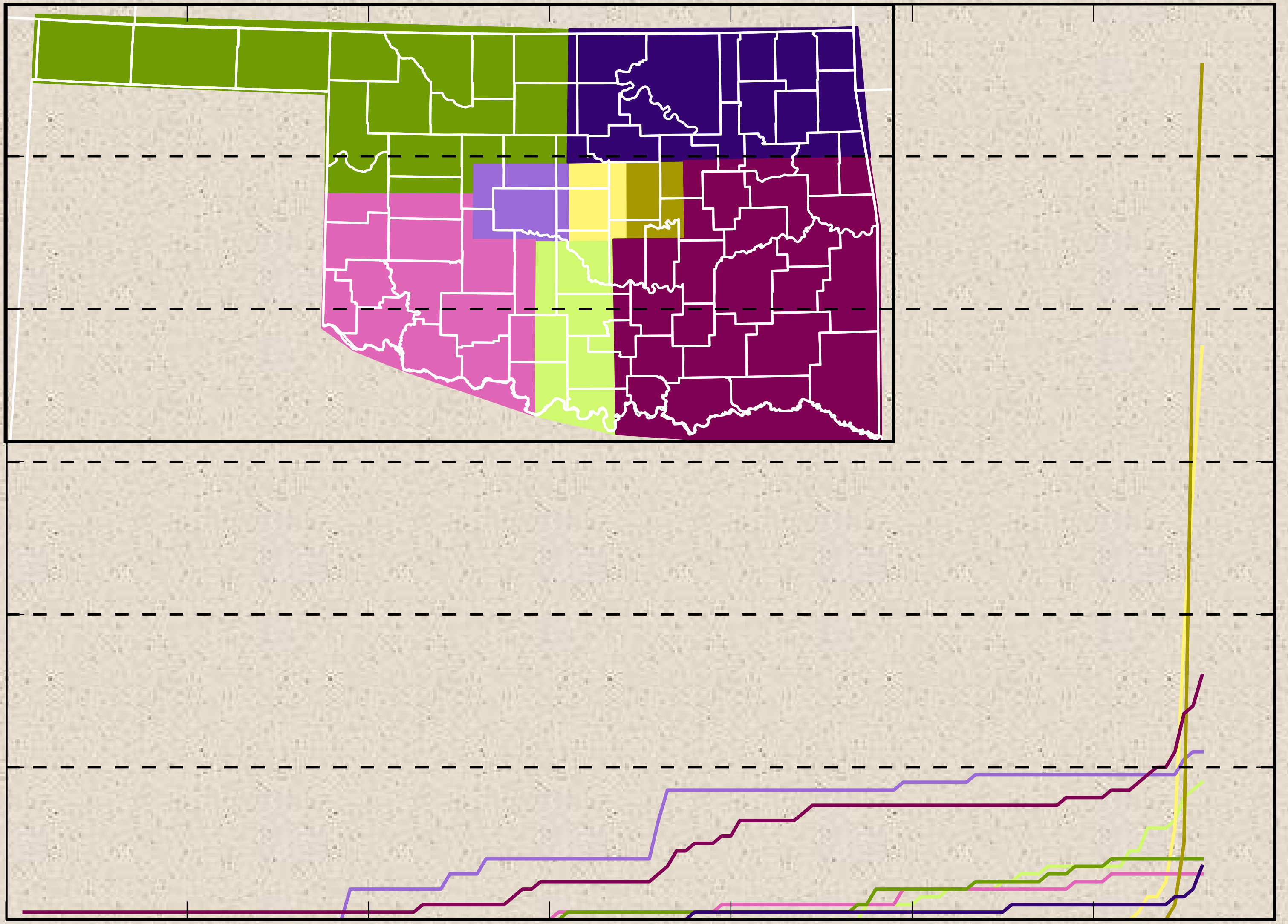
Induced Seismicity from Hydraulic Fracturing

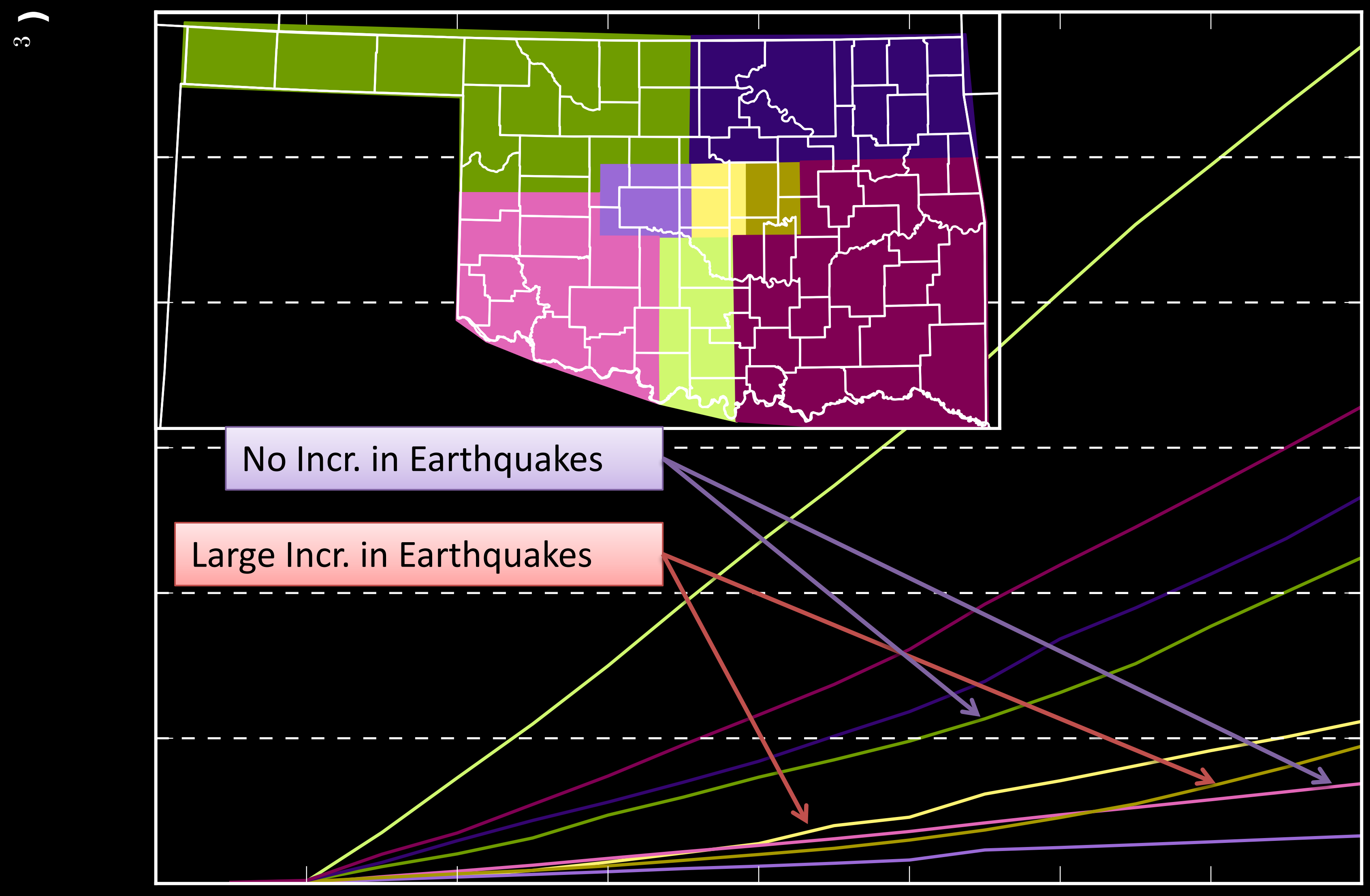
- Recent Cases from Oklahoma
  - Eola Field, Garvin County, ~100 earthquakes, M_{max}=2.9
  - Possible, Union City Field, Canadian County, ~10 earthquakes, M_{max}=3.4
  - Could be as large as 2% of completed wells in Oklahoma
- Other recent cases
  - Blackpool, United Kingdom, >50 earthquakes, M_{max}=2.3
  - Horn River Basin, British Columbia, >40 earthquakes, M_{max}=3.5



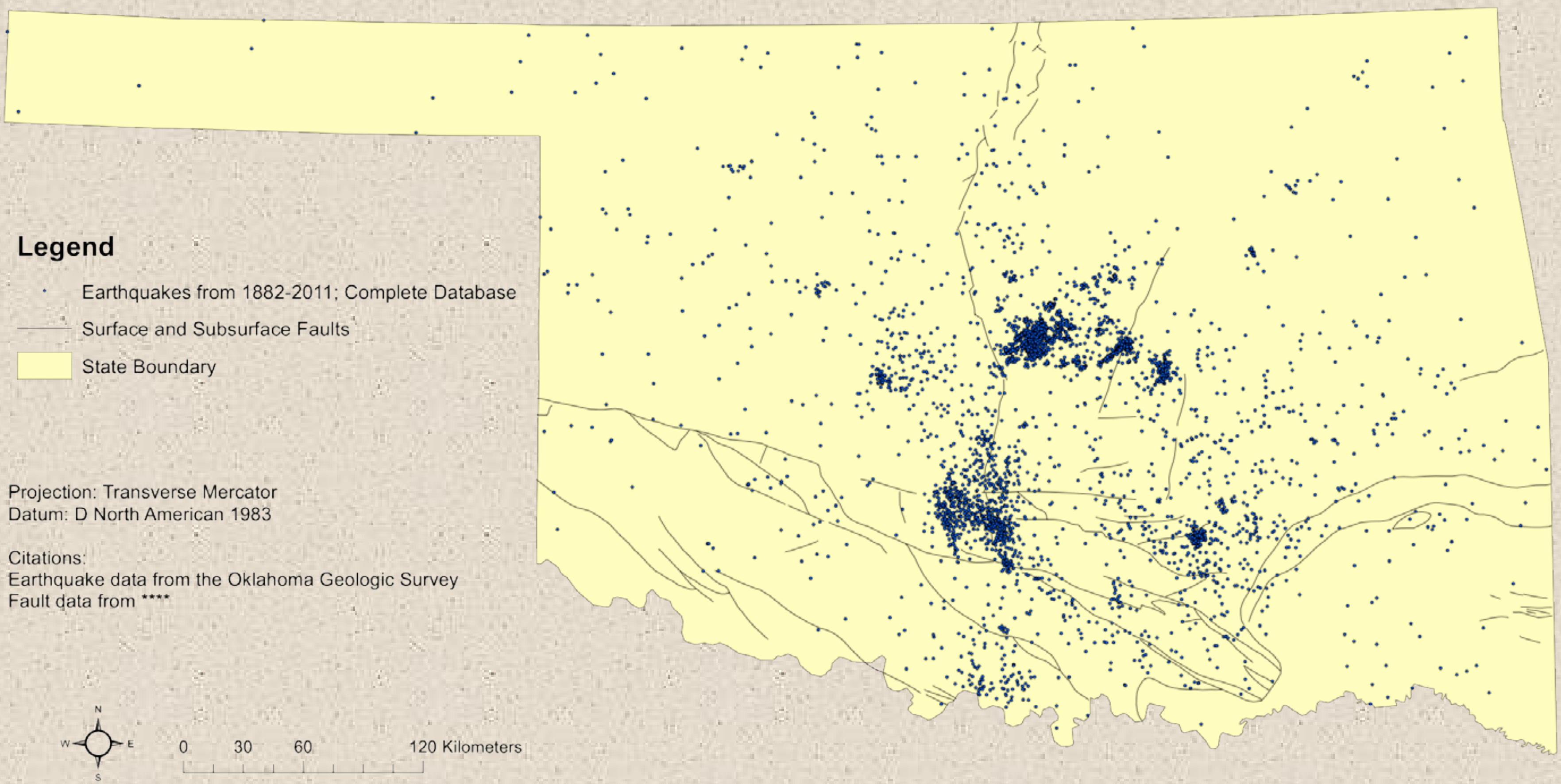
Number of Earthquakes in Oklahoma
100
80
60
40
20
0
M ≥ 3.0
5
1980
1985
1990
1995
2000
2005
2010
2015
Year

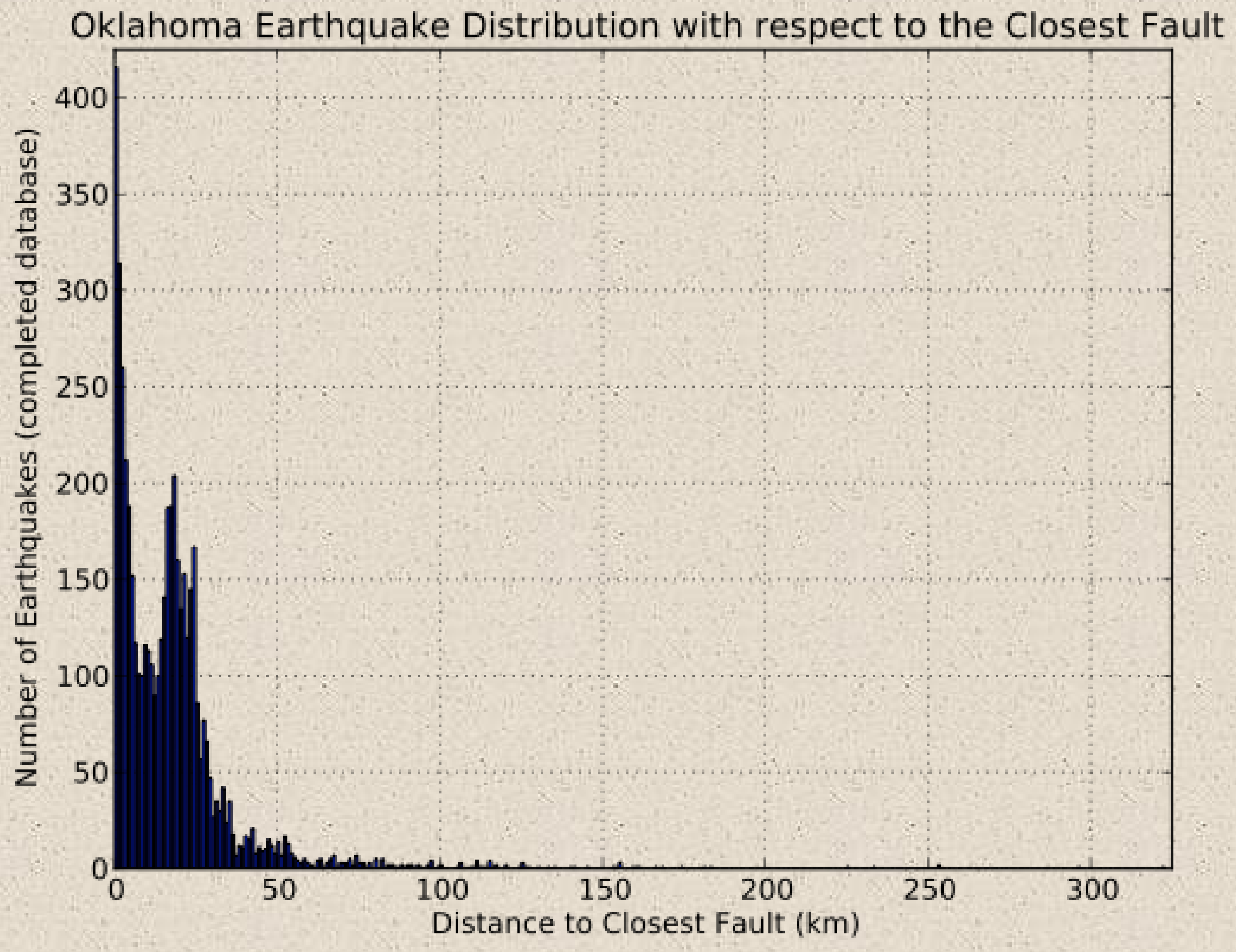
Oklahoma Earthquakes by Region



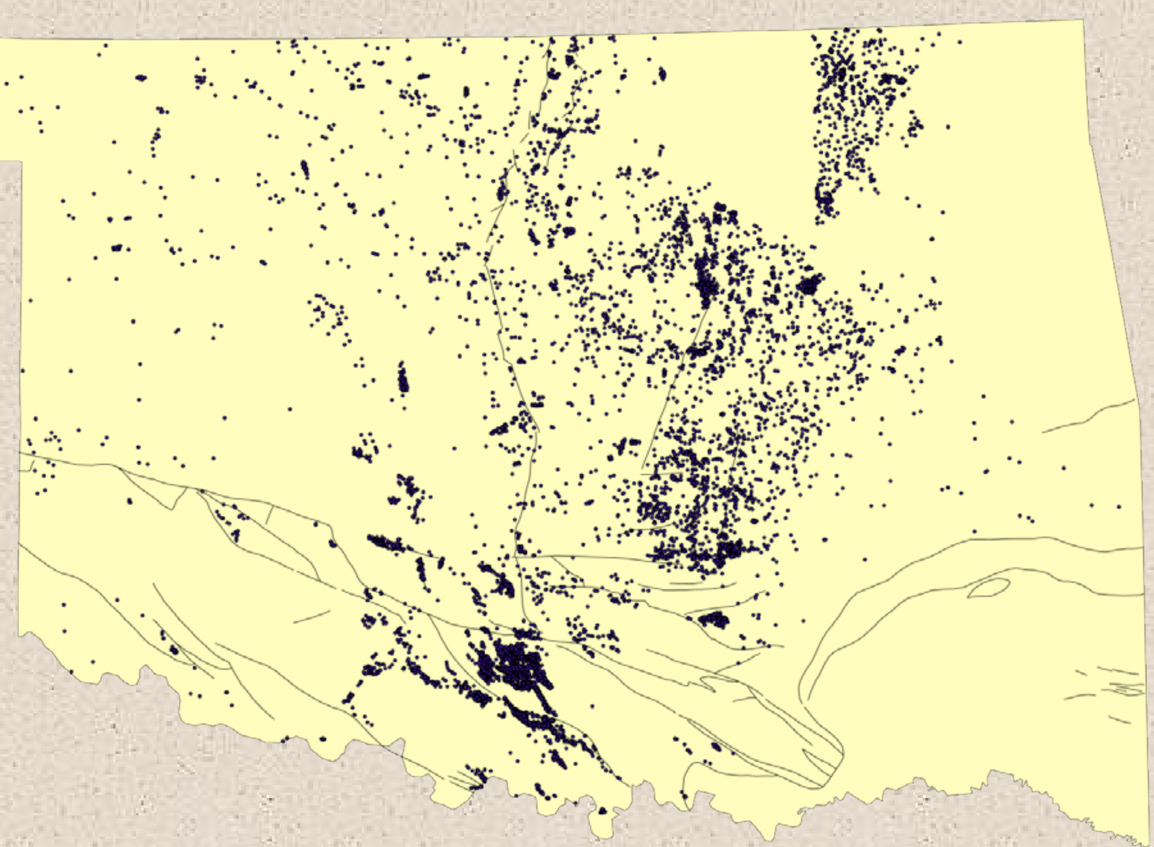

No Incr. in Earthquakes
Large Incr. in Earthquakes

Oklahoma Earthquake Distribution with respect to Faults




Oklahoma Earthquake Distribution with respect to the Closest Fault
Number of Earthquakes (completed database)
Distance to Closest Fault (km)
0
50
100
150
200
250
300
350
400

Oklahoma Injection Wells Distribution with respect to Faults



Legend

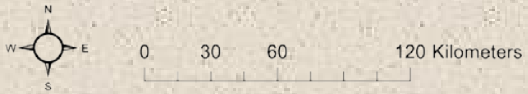
2010 UIC Wells

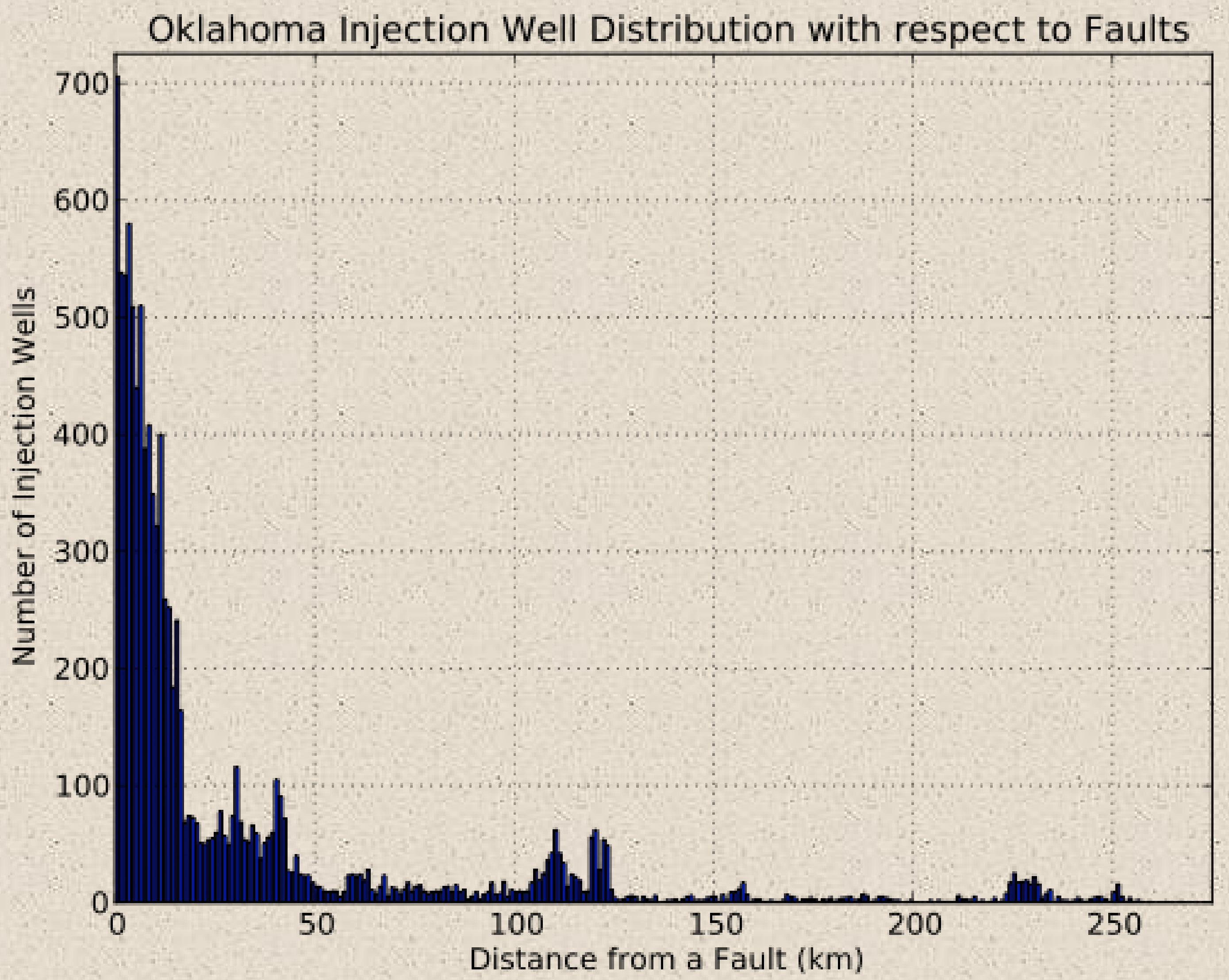
Surface and Subsurface Faults

State Boundary

Projection: Transverse Mercator
Datum: D North American 1983

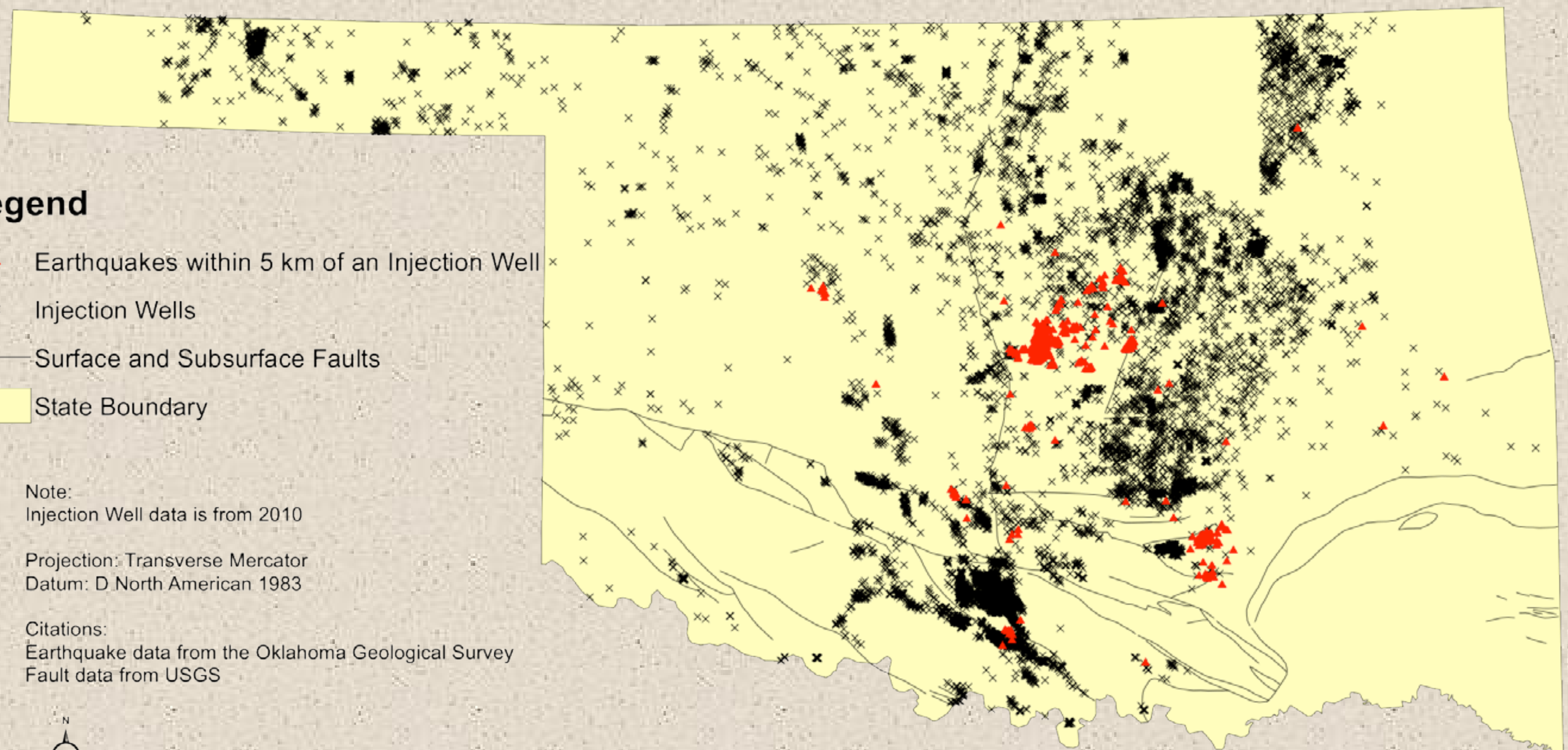
Citations:
Earthquake data from the Oklahoma Geological Survey
Fault data from ****





Oklahoma Injection Well Distribution with respect to Faults
Number of Injection Wells
Distance from a Fault (km)
0
100
200
300
400
500
600
700
0
50
100
150
200
250

Oklahoma Injection Wells and Earthquake Distribution in 2010



Legend

- Earthquakes within 5 km of an Injection Well
- Injection Wells
- Surface and Subsurface Faults
- State Boundary

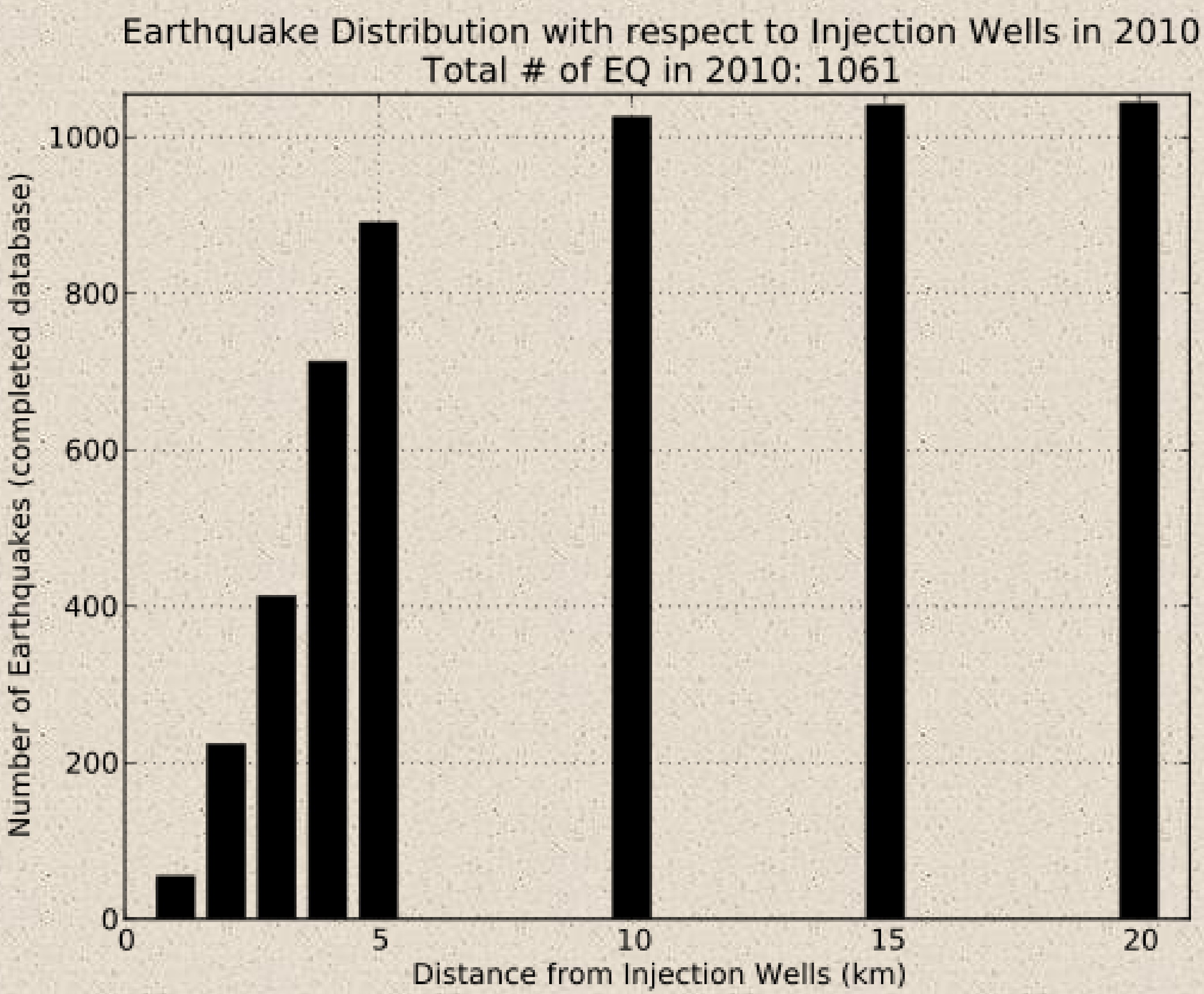
Note:
Injection Well data is from 2010

Projection: Transverse Mercator
Datum: D North American 1983

Citations:
Earthquake data from the Oklahoma Geological Survey
Fault data from USGS

N
W E
S

0 30 60 120 Kilometers

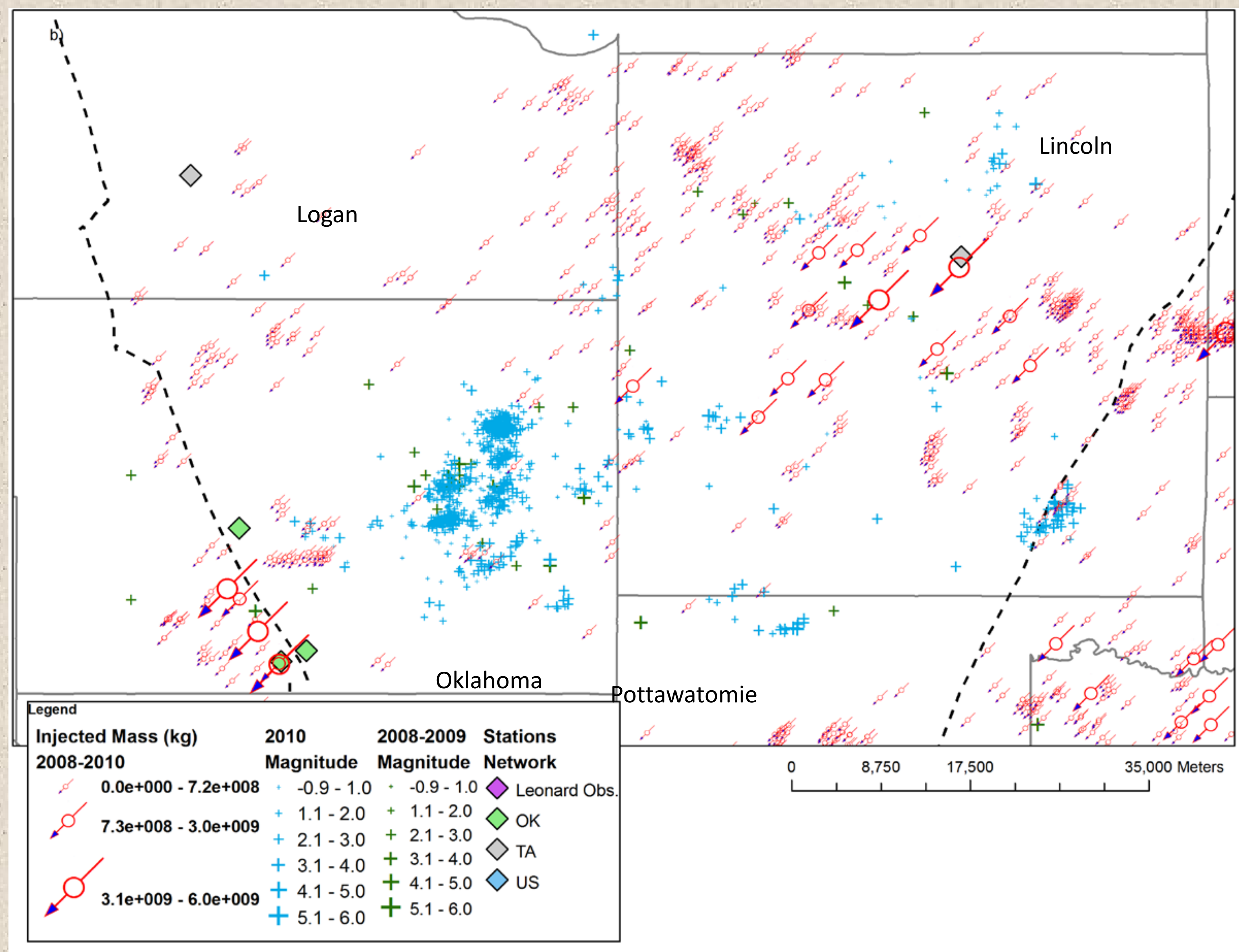


Earthquake Distribution with respect to Injection Wells in 2010
Total # of EQ in 2010: 1061
Number of Earthquakes (completed database)
0
200
400
600
800
1000
0
5
10
15
20
Distance from Injection Wells (km)

Induced Seismicity from Water Disposal

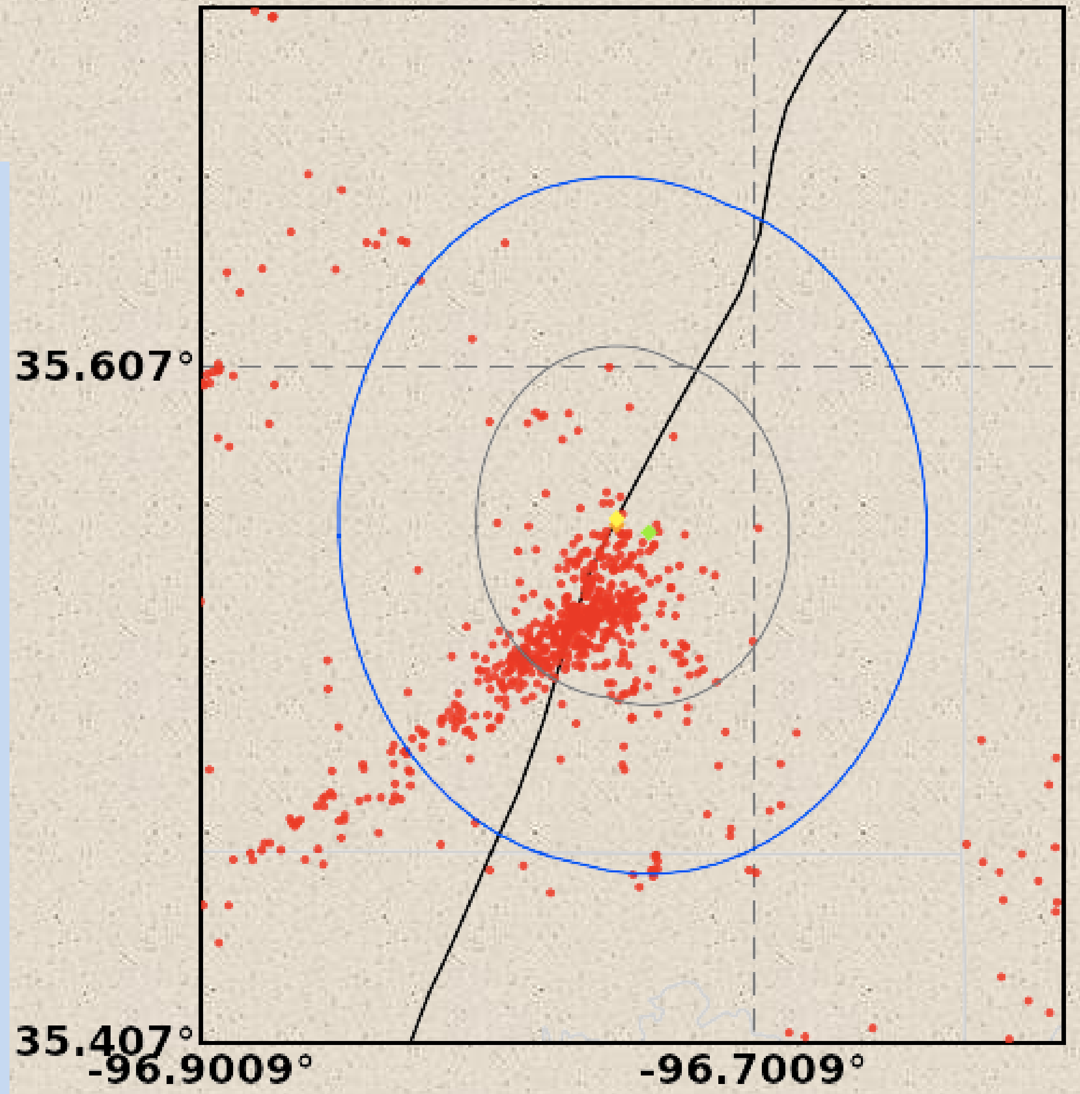
- Possible Cases from Oklahoma
  - Jones Earthquake Swarm, ~1800 earthquakes, M_{max}=4.0, large volume wells within 8-12 miles
    - Earthquake recurrence statistics are not similar to the rest of Oklahoma
    - Larger variation of active fault-plane orientations than expected
  - M5.7 Prague Earthquake, 3 UIC Class II wells within ~1 mile
  - Examining other possible cases

Fluid Injection in Central, OK

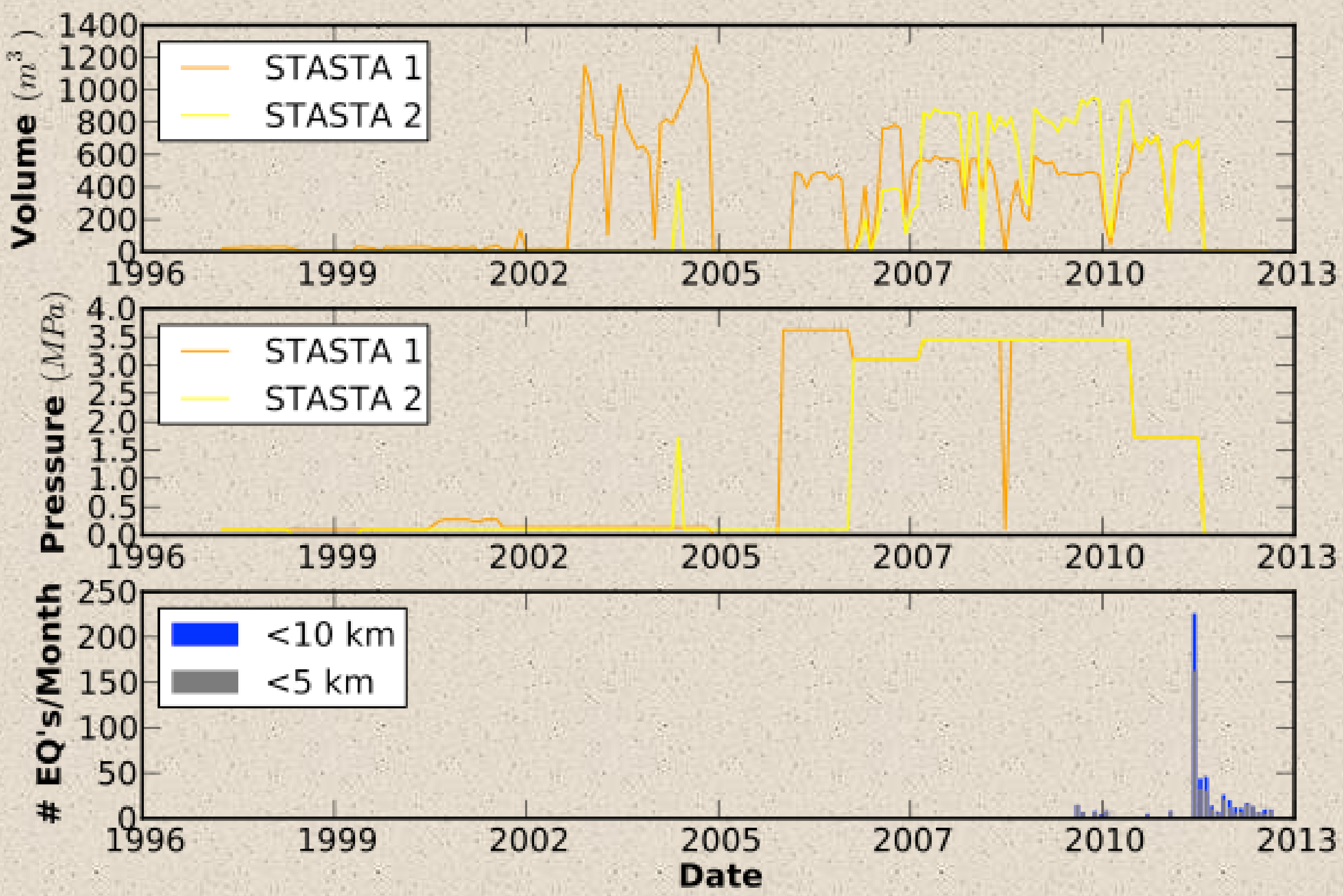


M5.7 Prague Earthquake

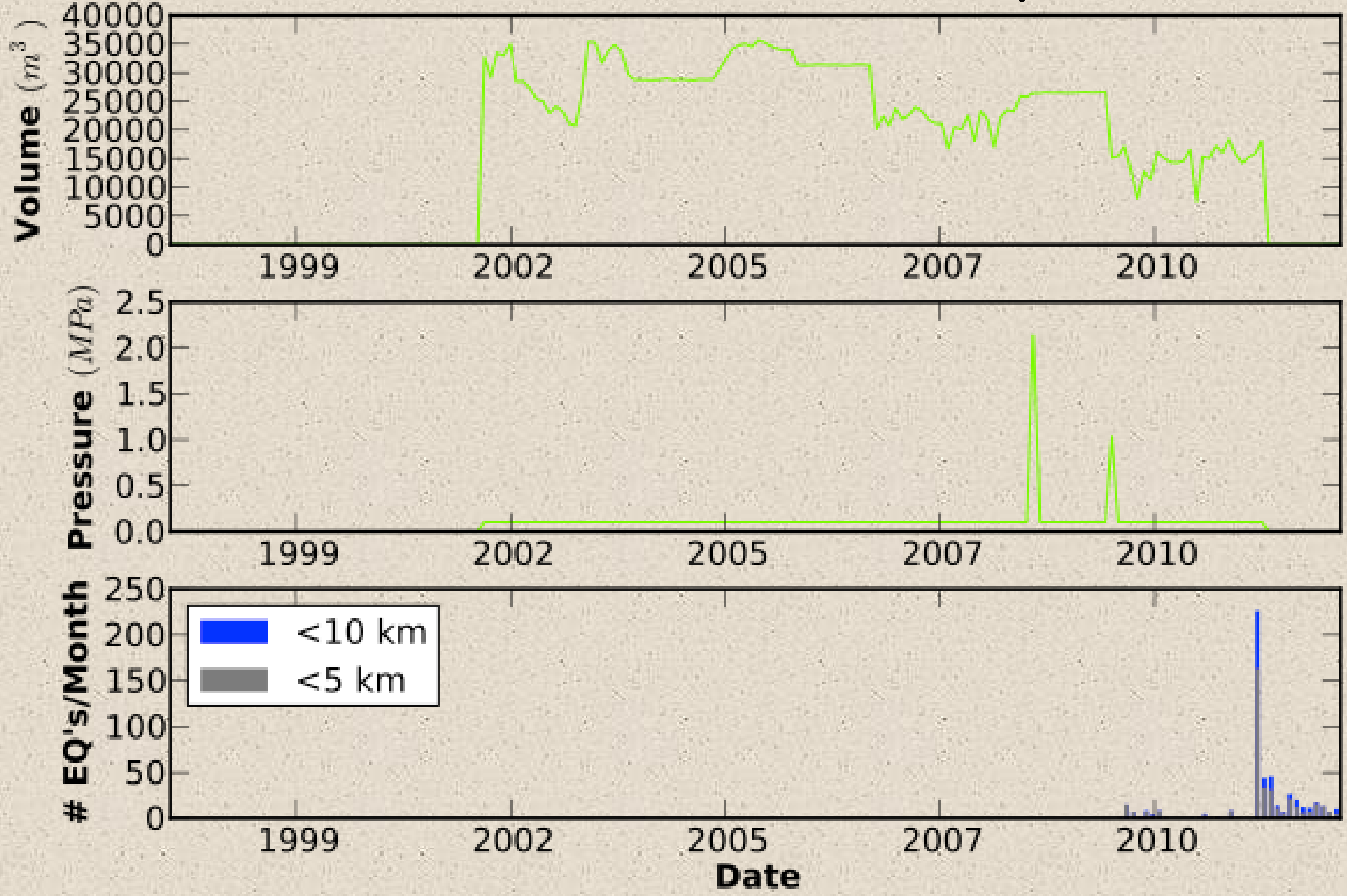
- November 5, 2011
- Suggested by Keranen et al. (in review in Geology) as being induced from injection from 3 wells
- Main shock occurred on a splay of the Wilzetta fault which is consistent to be active in the regional stress-field
- Earthquakes have the characteristics typical of a natural aftershock sequence
- It is possible that these earthquakes were triggered, but not certain



STASTA #1&2 Wells and Earthquakes



STASTA #1&2 Wells and Earthquakes



Conclusions

- Given the spatial distribution of both UIC Class II wells and earthquakes with respect to faults it is possible some earthquakes may be induced
  - But there can also be spatial coincidences
- Triggered earthquakes from hydraulic fracturing clearly demonstrate their is potential for induced seismicity in Oklahoma
- Historical earthquakes suggest stresses are sufficient to have triggered earthquakes
- Long injection histories, monthly records and multiple wells complicate the identification of triggered earthquakes from UIC Class II wells
- Need better rigorous scientific methods to discriminate natural seismicity from induced.

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QUESTIONS & COMMENTS

PRELIMINARY REPORT ON THE NORTHSTAR #1 CLASS II INJECTION WELL AND THE SEISMIC EVENTS IN THE YOUNGSTOWN, OHIO AREA

Tom Tomastik, Geologist, ODNR, Division of Oil and Gas Resources Management

PURPOSE AND SCOPE OF THE REPORT

- Site characterization and geology
- History of Ohio’s Class II injection program
- Permitting and drilling history of the Northstar Class II wells
- Brief history of seismic monitoring
- Preliminary interpretation of the data
- Evaluation of the data and downhole testing

SEISMICITY

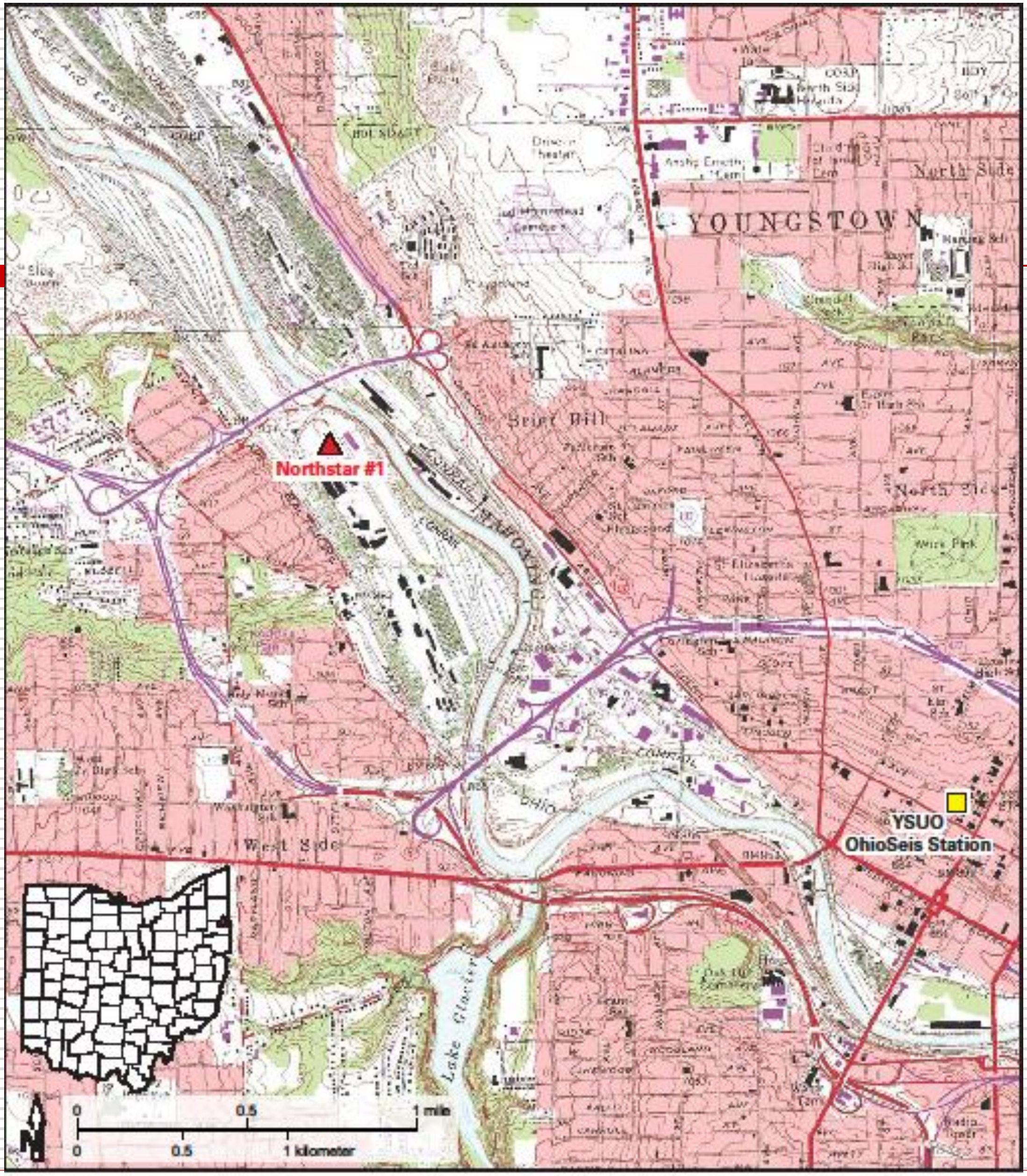
- Seismicity induced by human activities has been well documented
- Associated with mining, lake filling, geothermal energy-relate injection, oil and gas production activities, and injection disposal operations

FUNDAMENTAL QUESTIONS OF INDUCED SEISMICITY (FROM DAVIS AND FROHLICH, 1993)

- Are the events the first known earthquakes of this character in the region?
- Is there a clear correlation between injection and seismicity?
- Are epicenters near wells (within five kilometers)?
- Do some earthquakes occur at or near injection depths?
- If not, are there known geologic structures that may channel flow to the sites of earthquakes?
- Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
- Are changes in fluid pressure at hypocenter location sufficient to encourage seismicity?

WELL LOCATION

- The Northstar #1 injection well is located in an industrial district of NW Youngstown in Mahoning County, Ohio
- Well site is on a reclaimed iron foundry



YOUNGSTOWN
Northstar #1
YSUO
OhioSeis Station
Briar Hill
North Side
West Side
Lake Glacier
0
0.5
1 mile
0
0.5
1 kilometer

NORTHSTAR #1 WELL

- Original drilled as a stratigraphic test – first deep well in Mahoning County
- Drilled to 9184 feet on April 13, 2010
- Permit to convert to Class II injection issued on July 12, 2010
- Injection commenced on December 22, 2010

INJECTION WELL PERMIT

DEPARTMENT OF NATURAL RESOURCES

RESOURCES MANAGEMENT

WELL PERMIT

API WELL NUMBER

34-099-2-3127-00-00

OWNER NAME, ADDRESS

D & L ENERGY INC (Owner #: 2851)
2761 SALT SPRINGS RD
YOUNGSTOWN OH 44509

DATE ISSUED 7/12/2010

PERMIT EXPIRES 7/12/2011

TELEPHONE NUMBER (330) 792-9524

IS HEREBY GRANTED PERMISSION TO: Convert AND ABANDON WELL IF UNPRODUCTIVE

PURPOSE OF WELL: Water Injection - Disposal

COMPLETION DATE IF PERMIT TO PLUG:

DESIGNATION AND LOCATION:

LEASE NAME	NORTH STAR(SWIW #10)
WELL NUMBER	1
COUNTY	MAHONING
CIVIL TOWNSHIP	YOUNGSTOWN
TRACT OR ALLOTMENT	
SURFACE FOOTAGE LOCATION	5372'NL & 4080'EL OF TWP.
TARGET FOOTAGE LOCATION	

SURFACE NAD27
X: 2500822
Y: 534715
LAT: 41.12014
LONG: -80.6830t

TARGET NAD27

TYPE OF TOOLS: Air Rotary/Fluid Rotary

PROPOSED TOTAL DEPTH 9164 FEET

GROUND LEVEL ELEVATION 86? FEET

GEOLOGICAL FORMATION(S): KNOX-PRECAMBRIAN

SPECIAL PERMIT CONDITIONS: Salt Water Injection Well (Class II) Construction and Operating Conditions

CONDITIONALLY APPROVED CASING PROGRAM (SUBJECT TO APPROVAL OF THE OIL AND GAS WELL INSPECTOR):

CASING IN HOLE:
8-5/8" - 1010'
5-1/2" CASING 8215' CEMENTED TO A MINIMUM OF 300' ABOVE INJECTION ZONE
2-3/8" TUBING @ 8140' SET ON A PACKER @ 75' ABOVE INJECTION ZONE

This permit is NOT TRANSFERABLE. This permit, or an exact copy thereof, must be displayed in a conspicuous and easily accessible place at the well site before permitted activity commences and remain until the well is completed. Ample notification to inspector is necessary.

OIL AND GAS WELL INSPECTOR:

ROBERTS CARL (330) 451-0021
WAYNE SCHALK - Supervisor (330) 284-7038
DISTRICT # (330) 222 1527

INSPECTOR NOTIFICATION

The oil and gas inspector must be notified at least 24 hours prior to:

1. Commencement of site construction
2. Pit excavation and closure
3. Commencement of drilling, reopening, converting or plugback operations
4. Installation and cementing of all casing strings
5. BOP testing
6. Well stimulation
7. Plugging operations

The oil and gas inspector must be notified immediately upon:

1. Discovery of defective well construction
2. Detection of any natural gas or H2S gas during drilling in urban areas
3. Discovery of defective well construction during well stimulation
4. Determination that a well is a lost hole
5. Determination that a well is a dry hole

FIRE AND EMERGENCY NUMBERS:

FIRE: ( ) - 911

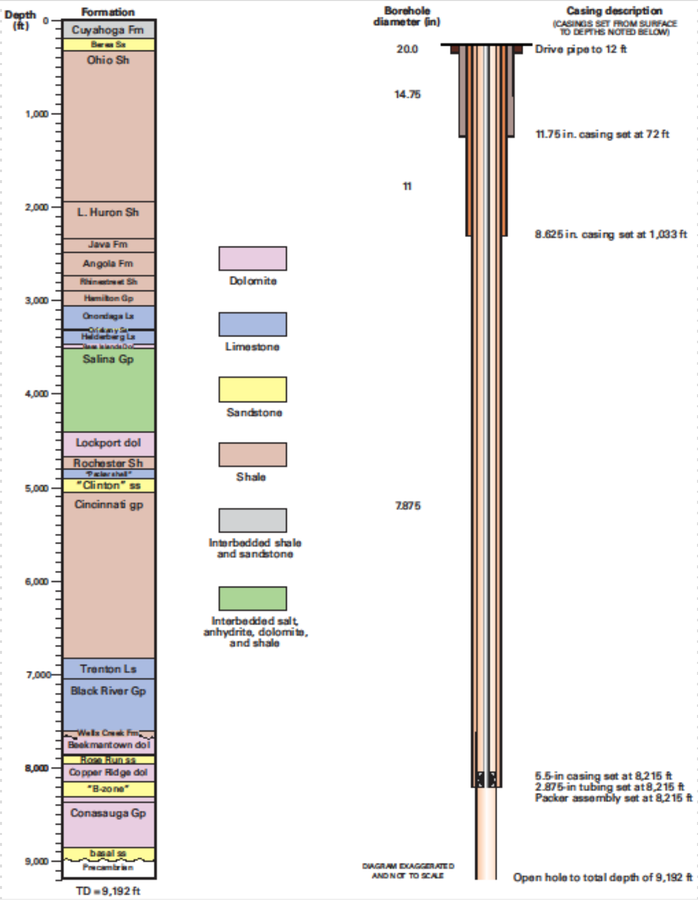
MEDICAL SERVICE: ( ) - 911

John F. Husted

CHIEF, DIVISION OF MINERAL RESOURCES MANAGEMENT

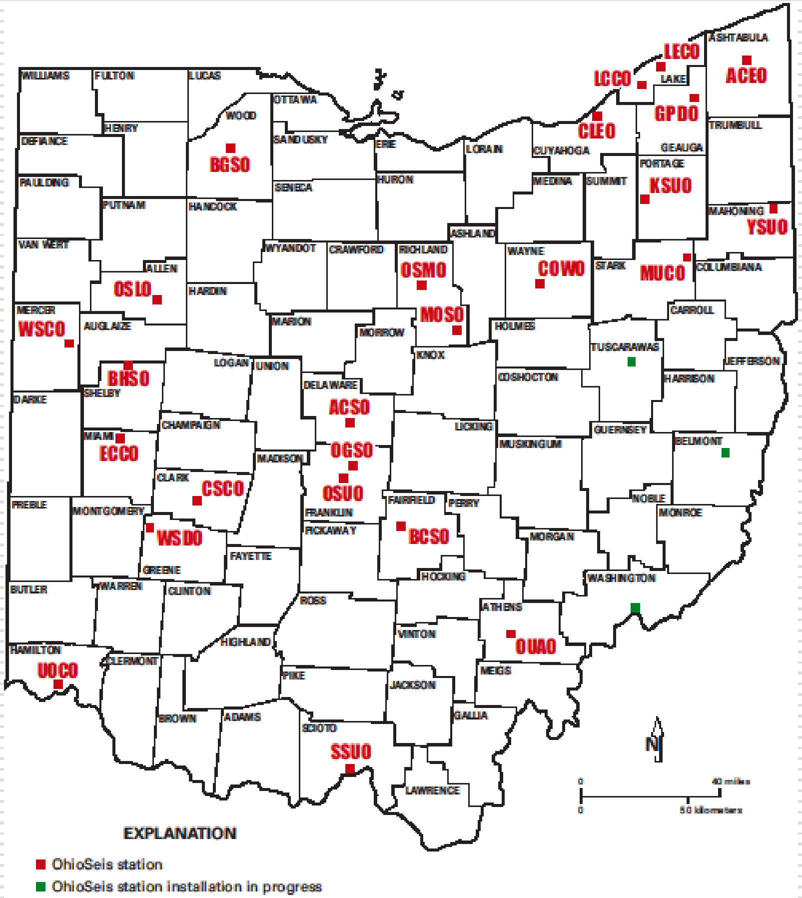
DNR 5806 (Rev. 5/10)

WELL CONSTRUCTION

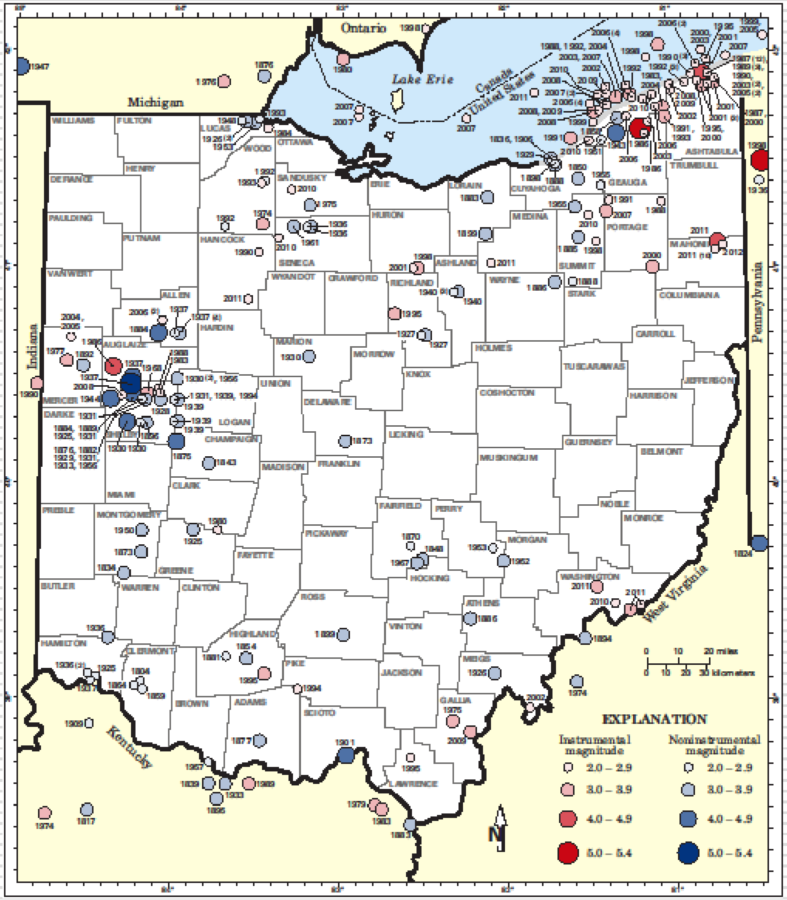


OHIO SEISMIC NETWORK

- Historically, seismic monitoring in Ohio was sporadic and seismic events below 3.0 were not accurately determined prior to 1999
- In 1999, Ohio Seismic Network was established
- Now have 29 stations established
- Youngstown State station joined the network in 2003



MAP OF EARTHQUAKES IN OHIO



SEISMIC EVENTS

- The first two seismic events happened on March 17, 2011
- Magnitude of 2.1 and 2.6
- Ten additional events occurred with the 4.0 event occurring on December 31, 2011

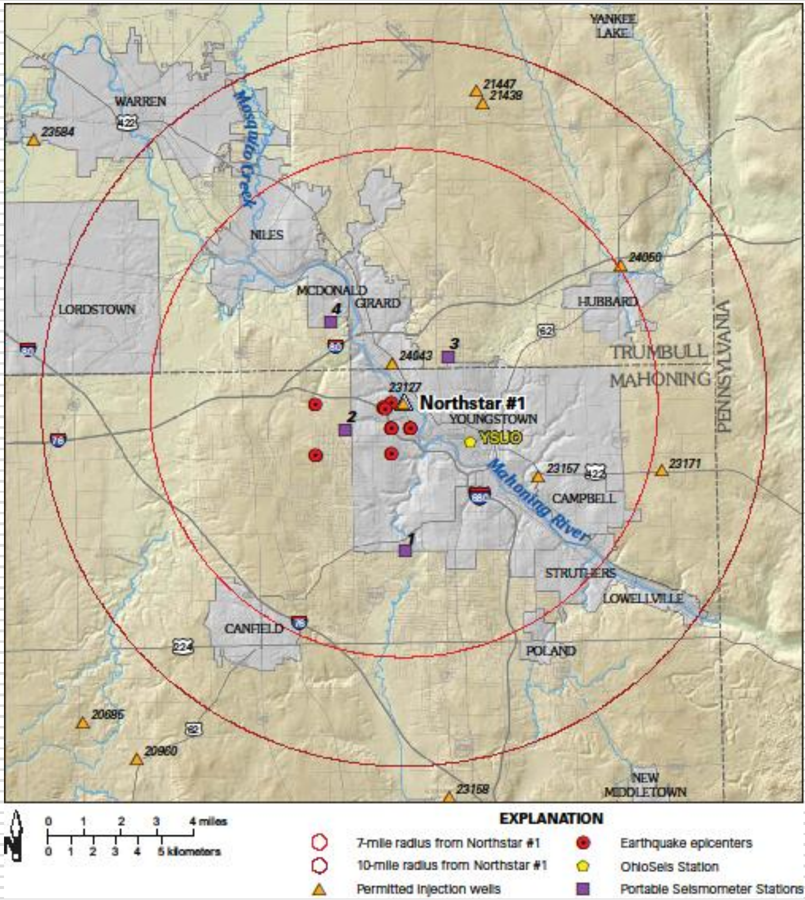


TABLE 5.—*Seismic events in Youngstown, Ohio, area recorded by the Ohio Seismic Network*

DATE	ORIG. TIME UTC	EPICENTER	MAGNITUDE	FELT
Mar. 17, 2011	10:42:20.22	41.11, -80.70	2.1	Not Felt
Mar. 17, 2011	10:53:09.51	41.11, -80.68	2.6	Felt (27 reports)
Aug. 22, 2011	08:00:31.50	41.12, -80.73	2.2	Not Felt
Aug. 25, 2011	19:44:20.99	41.10, -80.71	2.4	Not Felt
Sept. 02, 2011	21:03:26.20	41.12, -80.69	2.2	Felt (few)
Sept. 26, 2011	01:06:09.82	41.11, -80.69	2.6	Felt
Sept. 30, 2011	00:52:37.58	41.11, -80.69	2.7	Felt (300 reports)
Oct. 20, 2011	22:41:09.54	41.11, -80.68	2.3	Not Felt
Nov. 25, 2011	06:47:26.58	41.10, -80.69	2.2	Not Felt
Dec. 24, 2011	06:24:57.98	41.119, -80.694	2.7	Felt (90 reports)
Dec. 31, 2011	20:04:59.03	41.118, -80.693	4.0	Felt (more than 4,000)
Jan. 13, 2012	22:29:33.45	41.11, -80.69	2.1	Not Felt

SUBSURFACE TESTING

- After the September seismic events downhole testing was performed on the Northstar #1 injection well
- In October, a tracer survey was conducted and indicated that injection fluids were entering 26 multiple injection zones from 8215 to 8940 feet
- Requirement to plug back the Precambrian with cement
- Division of Oil and Gas Resources Management had performed 35 unannounced inspections at the Northstar #1 injection well from April to December of 2011

PORTABLE SEISMIC STATIONS

- Four highly sensitive, portable seismic stations, on loan from Lamont-Doherty, were deployed in the epicentral area of seismic activity on December 1, 2011
- Prior to the emplacement of these portable stations, detailed epicenter and surface locations of the previous seismic events were not very accurate
- The portable stations recorded the December 24th and 31st events and were able to calculate accurate epicenters

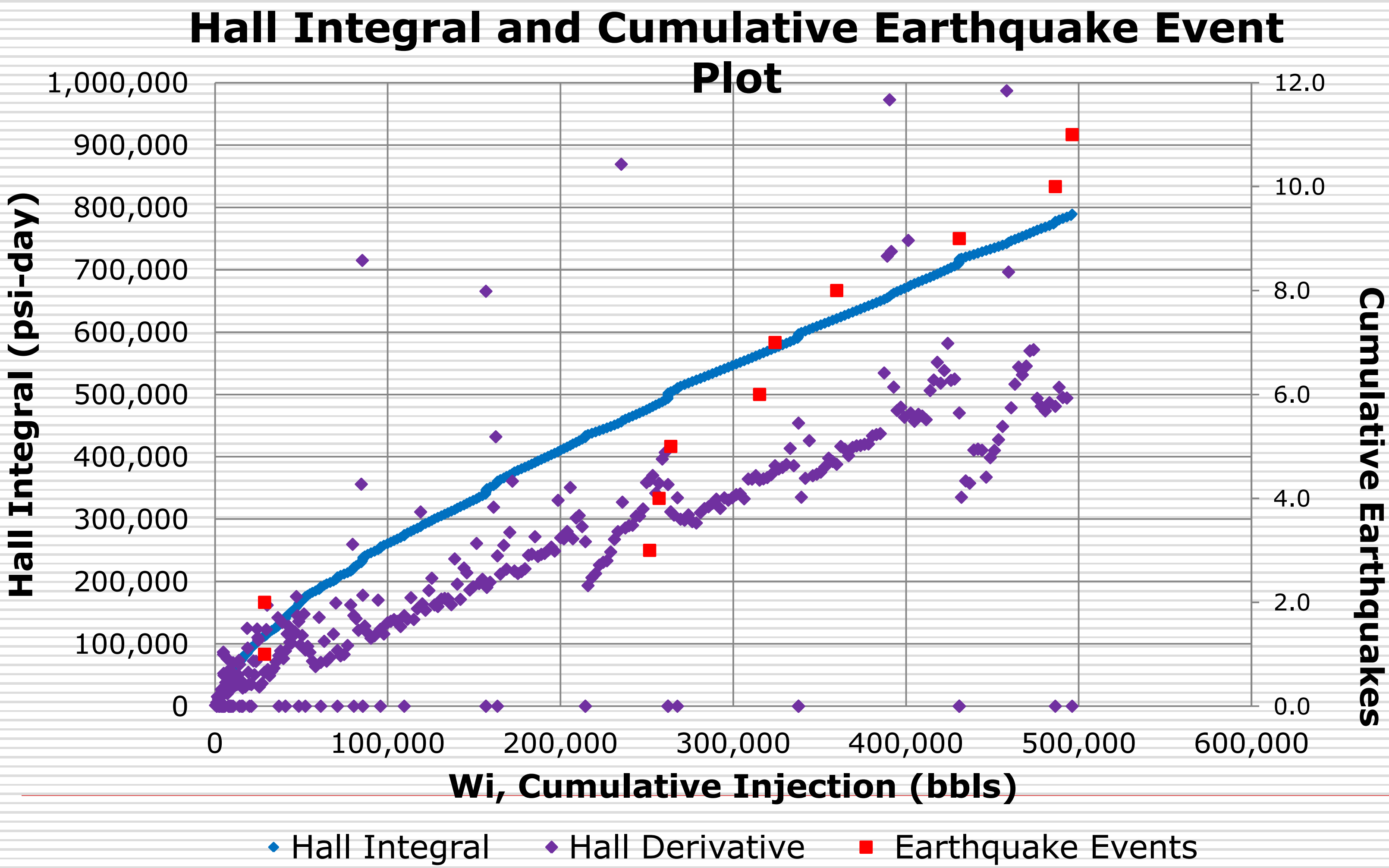
NORTHSTAR #1 INJECTION WELL

- After the December 24, 2011 seismic event, the portable seismic data was downloaded and evaluated
- On December 30th, at the request of the Director of ODNR, D & L Energy shut down the Northstar #1 well
- On December 31,2011, the 4.0 seismic event occurred and the Governor placed an indefinite moratorium on the other three drilled Northstar injection wells and one outstanding Northstar injection permit within a seven mile radius around the Northstar #1 injection well
- Additionally, all current Class II injection well permit applications were put on hold
- New Class II rules were implemented on October 1, 2012
- The first four new Class II permits were issued in November of 2012

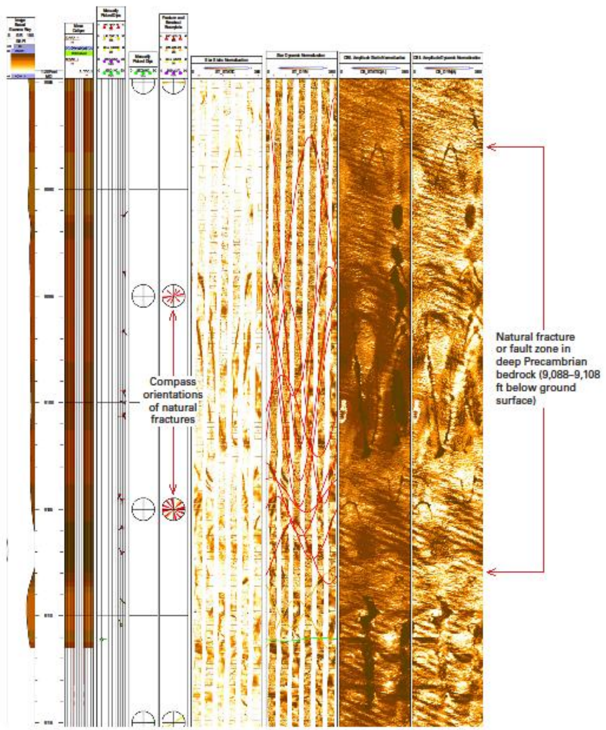
EVALUATION OF THE DATA

- Evaluations done by Lamont-Doherty on the seismic data indicates there may be a unknown fault within the Precambrian rocks near the Northstar #1 injection well
- Injection from the Northstar #1 well may have communicated with this potential fault and caused the seismic activity
- Data continues to be collected and evaluated

U.S. EPA REGION VI EVALUATION



ACOUSTIC AND RESISTIVITY IMAGE LOG



MEETINGS

- Meetings have been held with the operators of these five injection wells in the Youngstown area and proposals have been submitted to ODNR for review to address the seismicity issues and will be reviewed with ODNR's administration
- Final determinations as to the status of these injection wells will be made with the public's safety as a top priority

CONCLUSIONS OF THE REPORT

- Very difficult for all conditions to be met to induce seismic events
- There are 144,000 Class II injection wells in operation in the U.S. and less than 20 incidents of alleged induced seismicity
- Number of coincidental circumstances appear to make the compelling argument for the recent Youngstown-area seismic events may have been induced

COINCIDENTAL CIRCUMSTANCES?

- Seismic events started three months after the Northstar #1 well started injecting
- Events were clustered around the well
- Potential evidence of open fractures or high permeability zones within the Precambrian rocks
- Portable seismic stations were able to more accurately determine the surface and subsurface distances and depths of the seismic epicenters

CONTINUED RESEARCH

- Additional data is being collected and analyzed by experts
- Additional testing may be warranted to confirm preliminary findings
- Decisions must be based upon sound scientific information

CHANGES TO THE UIC PROGRAM

- Ohio's new Class II UIC rules went into effect on October 1, 2012
- These new rules can: prohibit drilling into the Precambrian rocks for Class II injection, possible collection of original downhole reservoir pressures, pressure fall-off testing, potential for conducting seismic surveys or seismic monitoring, minimum geophysical logging suite, automatic shut-off switches on injection pumps, continuous annulus pressure monitoring, and in depth geologic evaluation
- Rules are applied on a well-by-well basis – conversion vs. new well and depths of injection formations
- Ohio will continue to be proactive in its approach to induced seismicity

QUESTIONS

Induced Seismicity Potential in Energy Technologies

Robin K. McGuire
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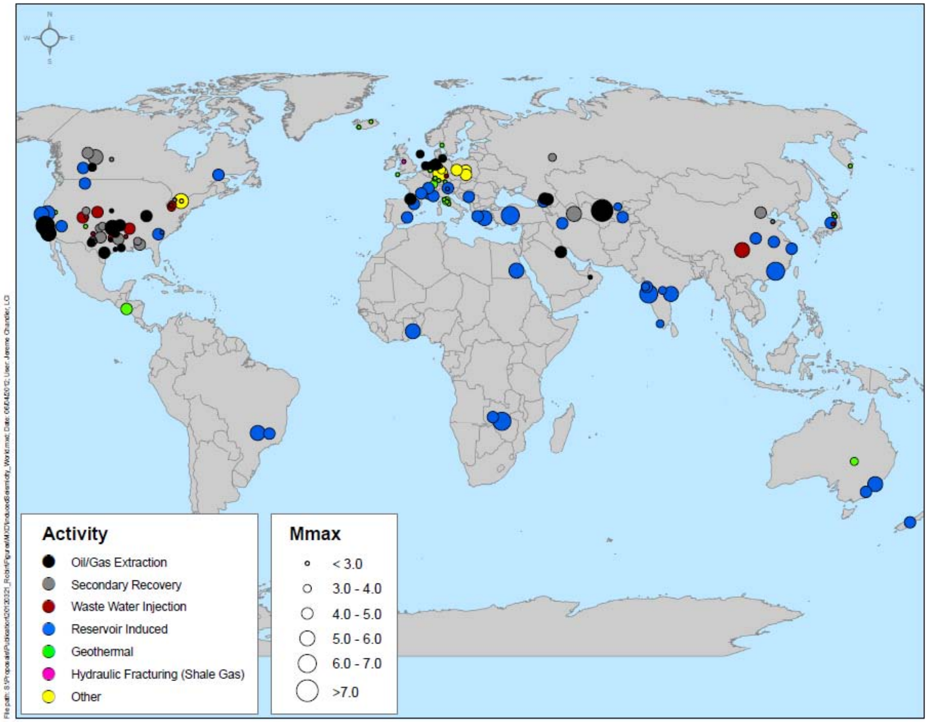
Boulder, Colorado

Committee on Induced Seismicity Potential in Energy Technologies, National Research Council

Sponsor:
US Department of Energy

Report released June 2012

Background



Source: NRC, 2012

- A number of seismic events apparently related to fluid injection for energy development occurred during the past 6 years, for example:

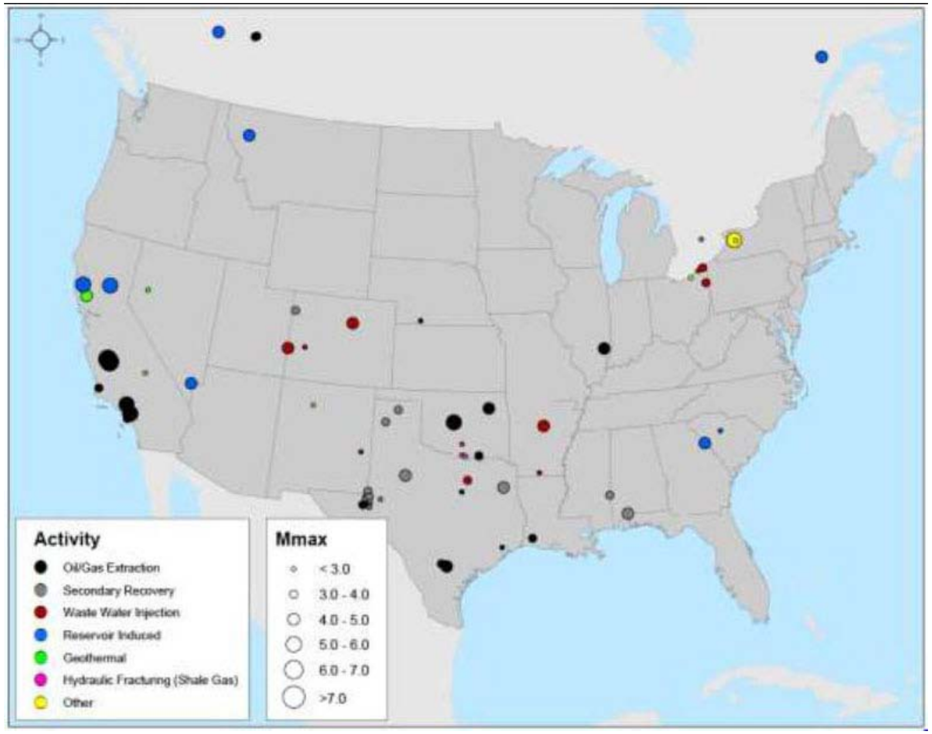
  - Basel, Switzerland, 2006, Enhanced geothermal system (M 3.4)

  - Dallas-Ft. Worth airport area, 2008-09, Waste water disposal from shale gas development (M 3.3)

  - Blackpool, England, 2011, Hydraulic fracturing (shale gas) (M 2.3)

- Public concern about these kinds of events prompted Senator Bingaman to ask Secretary Chu to request a study by the National Research Council on “Induced Seismicity in Energy Technologies”

Background (cont.)



Source: NRC, 2012

- The committee compiled a database of induced earthquakes (well-documented and probable) from the technical literature.
- The committee did not distinguish between "induced" seismicity and "triggered" seismicity

Statement of Task

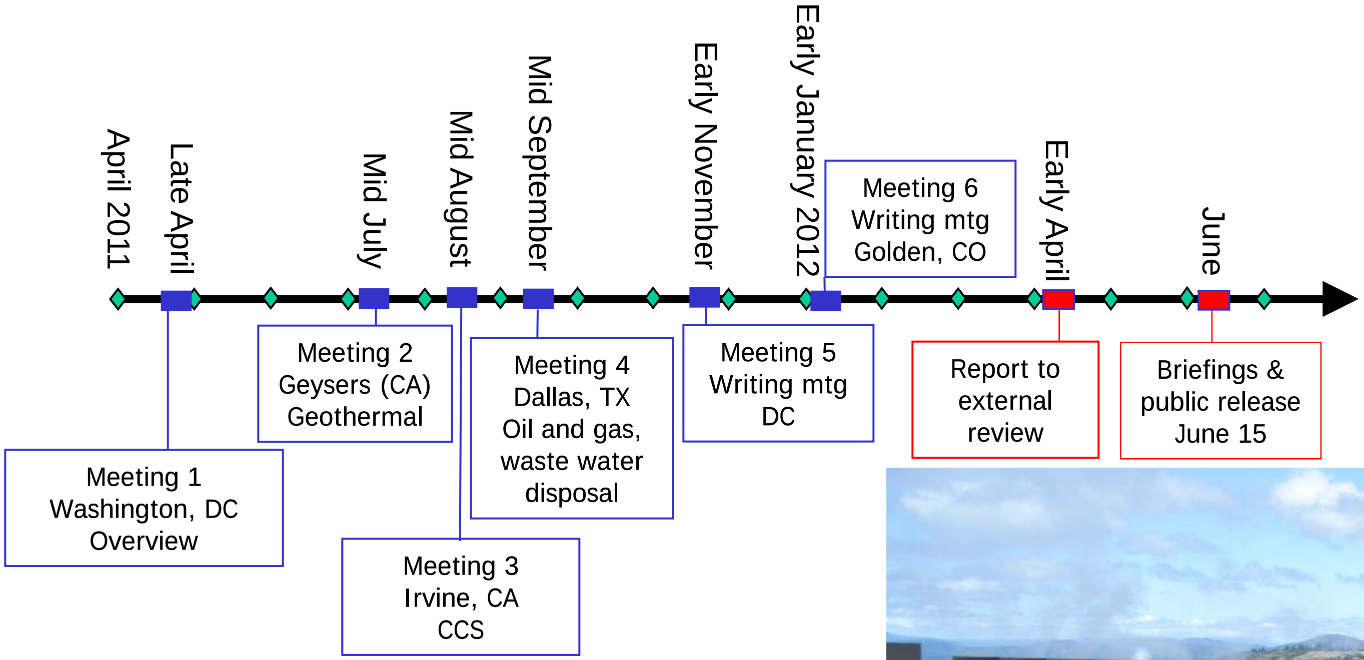
This study will address the potential for felt induced seismicity of geothermal systems, oil and gas production including enhanced oil recovery and hydraulic fracturing for shale gas production, and carbon capture and storage (CCS) and specifically will:

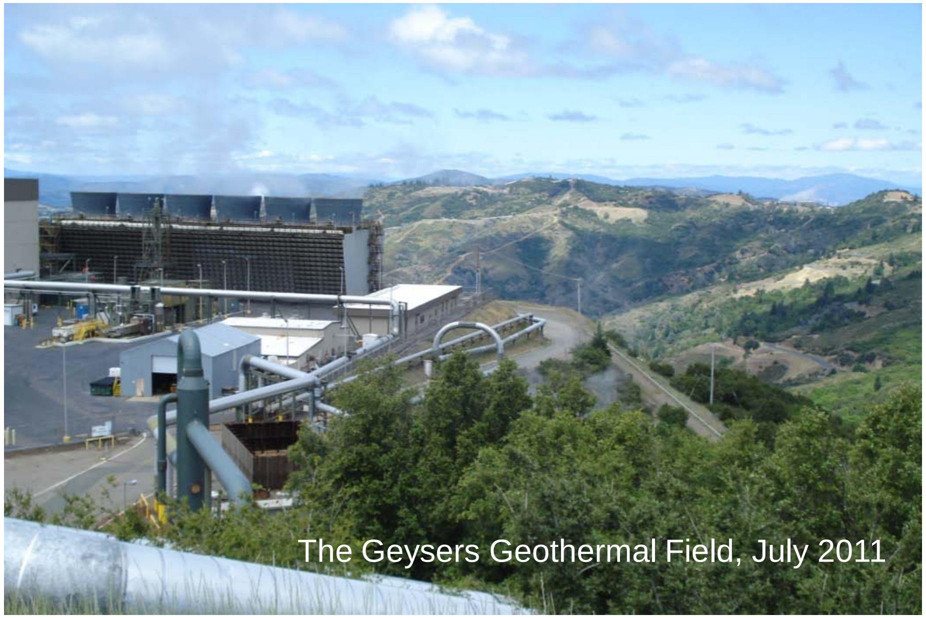
- summarize the current state-of-the-art knowledge on the possible scale, scope and consequences of seismicity induced during the injection of fluids related to energy production;
- identify gaps in knowledge and the research needed to advance the understanding of induced seismicity, its causes, effects, and associated risks;
- identify gaps and deficiencies in current hazard assessment methodologies for induced seismicity and research needed to close those gaps;
- identify and assess options for interim steps toward best practices, pending resolution of key outstanding research questions.

Report Overview

- Introduction to induced seismicity and its history
- Types and causes of induced seismicity
- Induced seismicity of energy technologies
  - Geothermal
  - Oil and gas (including EOR and shale gas recovery)
  - Waste water injection
  - Carbon capture and sequestration (CCS)
- Government roles and responsibilities
- Understanding hazard and risk assessment to manage induced seismicity
- Steps toward best practices
- Findings, gaps, proposed actions, and research recommendations

Study Process





The Geysers Geothermal Field, July 2011

Photo: E. Eide, used with permission

Types and Causes of Induced Seismicity

- Induced seismic activity has been attributed to a range of human activities including:
  - Impoundment of large reservoirs behind dams
  - Controlled explosions related to mining or construction
  - Underground nuclear tests
  - *Energy technologies that involve injection or withdrawal of fluids from the subsurface*

Types and Causes of Induced Seismicity in Fluid Injection/Withdrawal for Energy Development

- The general mechanisms that create induced seismic events are well understood.

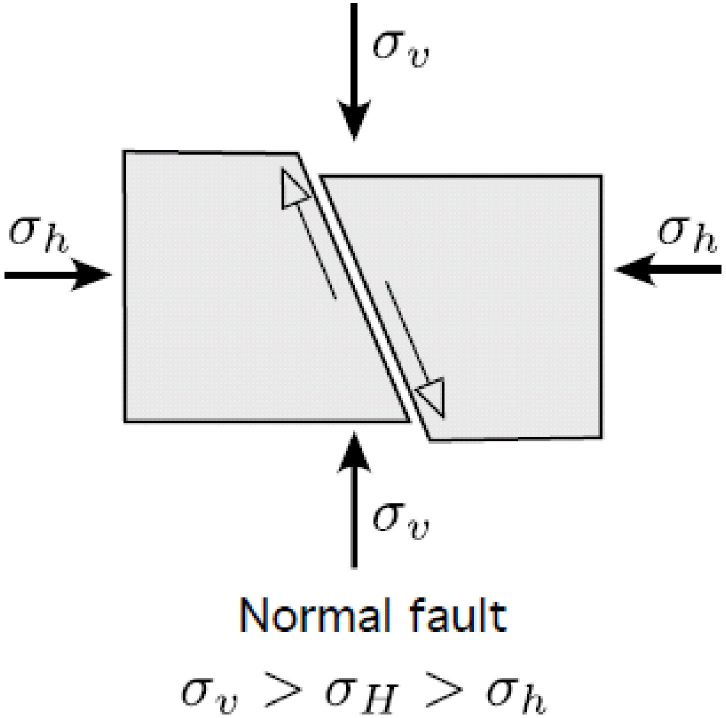
- However, we are currently unable to accurately predict the occurrence or magnitude of such events due to the lack of comprehensive data on complex natural rock systems and the lack of validated predictive models.

Types and Causes of Induced Seismicity in Fluid Injection/Withdrawal for Energy Development

- Induced seismicity is caused in most cases by change in pore fluid pressure and/or change in stress in the subsurface in the presence of:
  - faults with specific properties and orientations;
  - a critical state of stress in the crust.

- The factor that appears to have the most direct correlation in regard to induced seismicity is the net fluid balance — *the total balance of fluid introduced into or removed from the subsurface*.

- Additional factors may also influence the way fluids affect the subsurface.

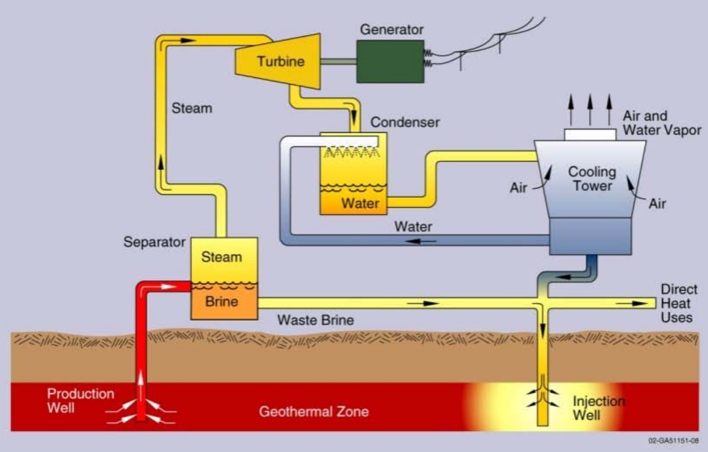


Source: NRC, 2012

Energy Technologies

- Geothermal energy development
  - *Vapor-dominated*
  - *Liquid-dominated*
  - *Enhanced geothermal systems (EGS)*
- Oil and gas development
  - *Oil and gas extraction (fluid withdrawal)*
  - *Secondary recovery (waterflooding)*
  - *Tertiary recovery (CO_2 flooding)*
  - *Hydraulic fracturing for shale gas*
- Waste water disposal wells
- Carbon capture and storage (CCS)

Energy Technologies—Geothermal Energy

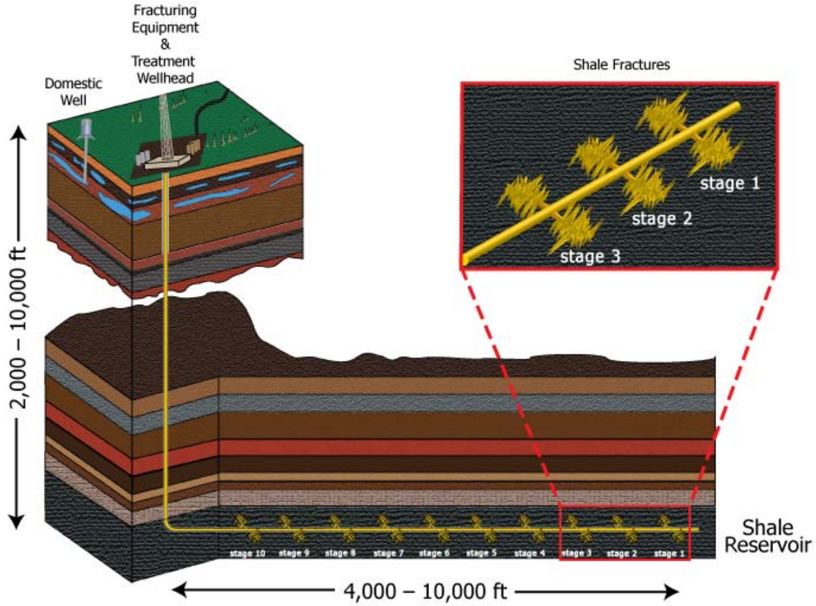


Source: Idaho National Laboratory

Flash Steam Power Cycle for liquid-dominated systems

- Vapor-dominated—primarily steam in pores and fractures of the rock
- Liquid-dominated—primarily hot water in the pores and fractures of the rock
- Enhanced geothermal systems (EGS)—“hot dry rock” requires fracturing to promote hot water circulation
- Operators attempt to keep balance between fluid volumes produced and fluids replaced by injection to maintain reservoir pressure
- *Different from other energy technologies in temperature of reservoir*

Energy Technologies — Oil and Gas



Adapted after Southwestern Energy, used with permission

Shale gas development

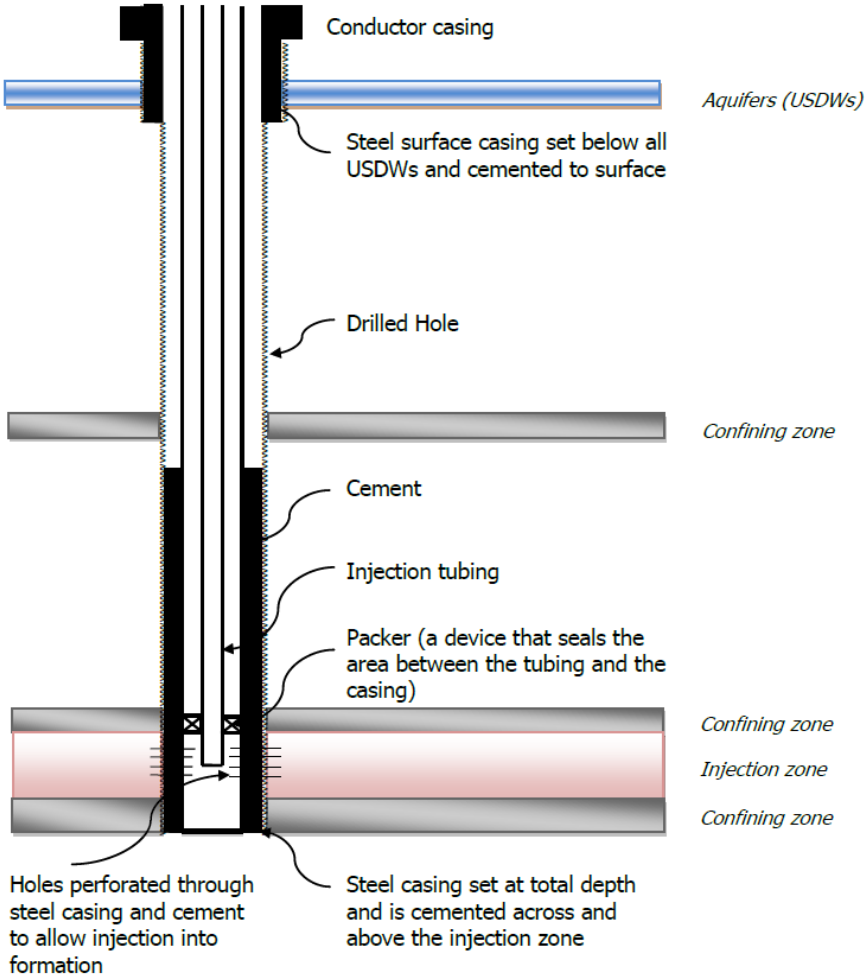
- Oil and gas withdrawal—removes large volumes of fluids over decades, usually with accompanying fluid injection

- Enhanced recovery—inject fluids (water, steam, CO_2, etc.) to extract remaining oil and gas
  - secondary recovery (often 'waterflooding')
  - tertiary recovery (enhanced oil recovery)

- Hydraulic fracturing a well for shale gas development—use horizontal drilling and hydraulic fracturing to create fractures for gas to migrate to a well

- Oil and gas operators attempt to balance the fluid volumes produced with fluid injection to maintain reservoir pressure

Energy Technologies — Waste Water Disposal Wells

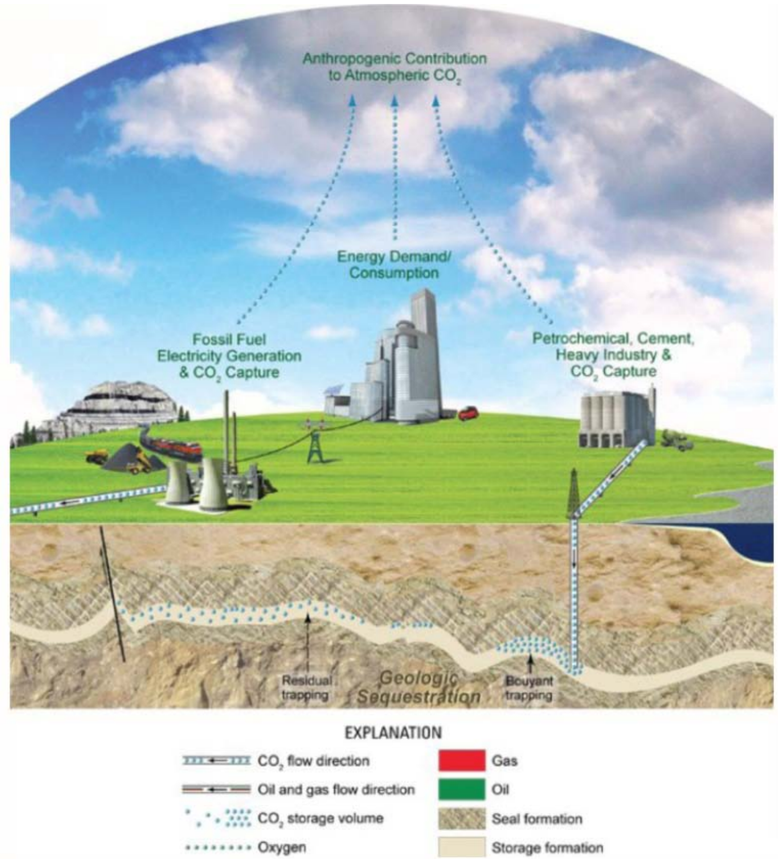


Source: NRC, 2012

- Fluid from flow back after hydraulic fracturing and waste fluid produced from conventional oil and gas production in the United States = over 800 billion gallons a year

- More than one third of the volume is managed through underground injection for permanent disposal in "Class II" wells, permitted by EPA and states with delegated authority

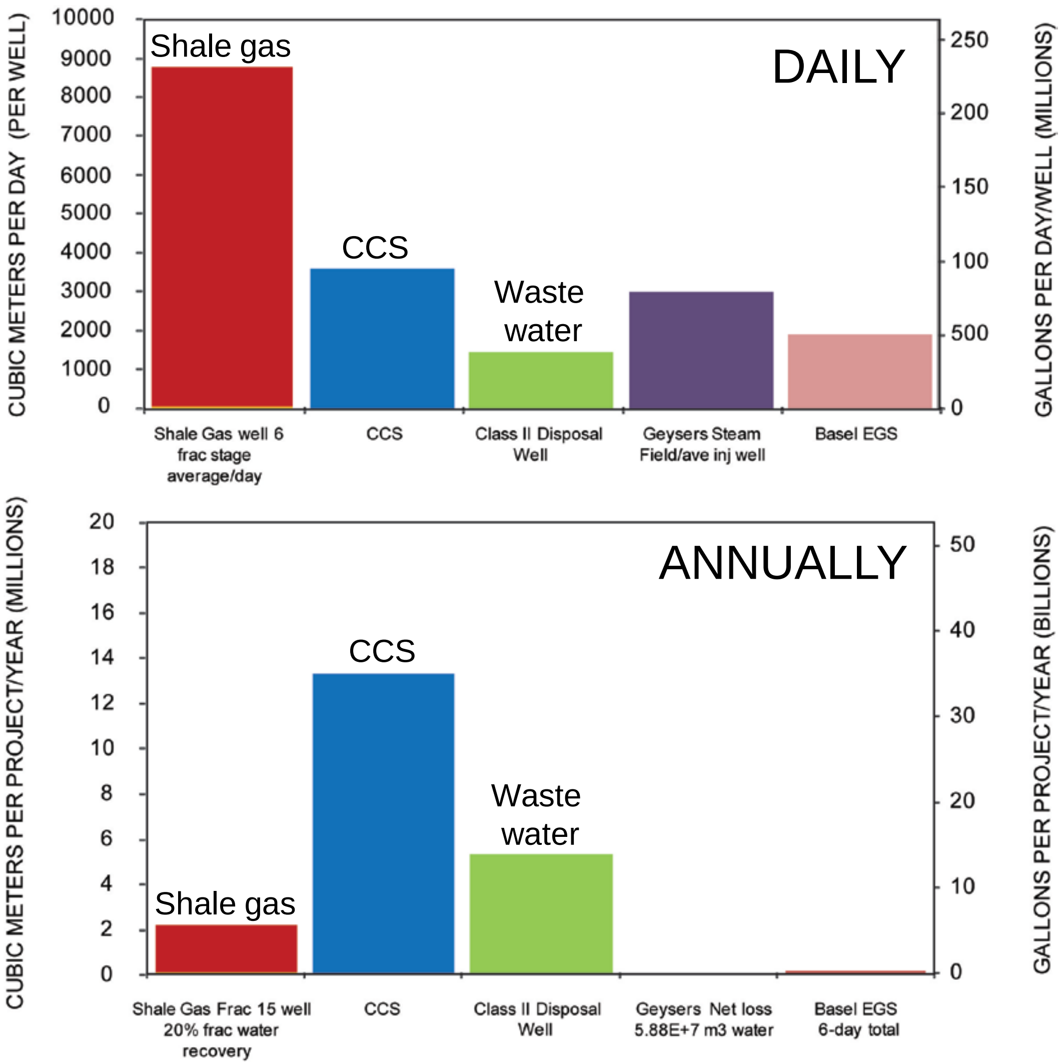
Energy Technologies—CCS



Source: USGS; Duncan et al. (2011)

- ❑ CO_2 can be captured, liquefied, and injected into various kinds of geological formations for permanent storage
- ❑ CO_2 remains a liquid (in "supercritical" phase) underground
- ❑ Small-scale commercial projects in operation (offshore Norway, onshore Algeria) inject about 1 million metric tonnes of CO_2 per year
- ❑ Regional partnerships in U.S. to test technologies and small-scale injection (Illinois)—plan to inject ~1 million metric tonnes of CO_2 per year
- ❑ Future projects expect to inject much greater than 1 million metric tonnes

Comparative Estimated Fluid Volumes for Energy Technologies



Source: NRC, 2012

- ❑ Daily fluid volumes injected are highest for hydraulic fracturing — 8,500 m^3
- ❑ Annual fluid volumes injected are highest for proposed CCS projects (13,000,000 m^3) and then Class II waste water disposal wells (4,000,000 m^3)
- ❑ Geysers geothermal field records net fluid loss annually

Historical Felt Seismic Events Caused by or Likely Related to Energy Technologies in U.S.

Energy Technology	Number of **Current** Projects	Number of **Historical** Felt Events	**Historical** Number of Events M≥4.0	Locations of Events M≥2.0
Geothermal				
Vapor-dominated (The Geysers)	1	300-400 per year since 2005	1 to 3	CA
Liquid-dominated	23	10-40 per year	Possibly one	CA
EGS	~8 pilot	2-10 per year	0	CA
Oil and gas				
Withdrawal	~6,000 fields	20 sites	5	CA, IL, NB, OK, TX
Secondary recovery (water flooding)	~108,000 wells today	18 sites	3	AL, CA, CO, MS, OK, TX
EOR	~13,000 wells today	None known	None known	None known
Hydraulic fracturing for shale gas recovery	~35,000 wells today	1 sites	0	OK
Waste water disposal wells (Class II)	~30,000 wells today	8 sites	7	AR, CO, OH,TX
Carbon capture and storage (small scale)	2	None known	None known	None known

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Energy Technology Potential for Induced Seismicity — Summary Points

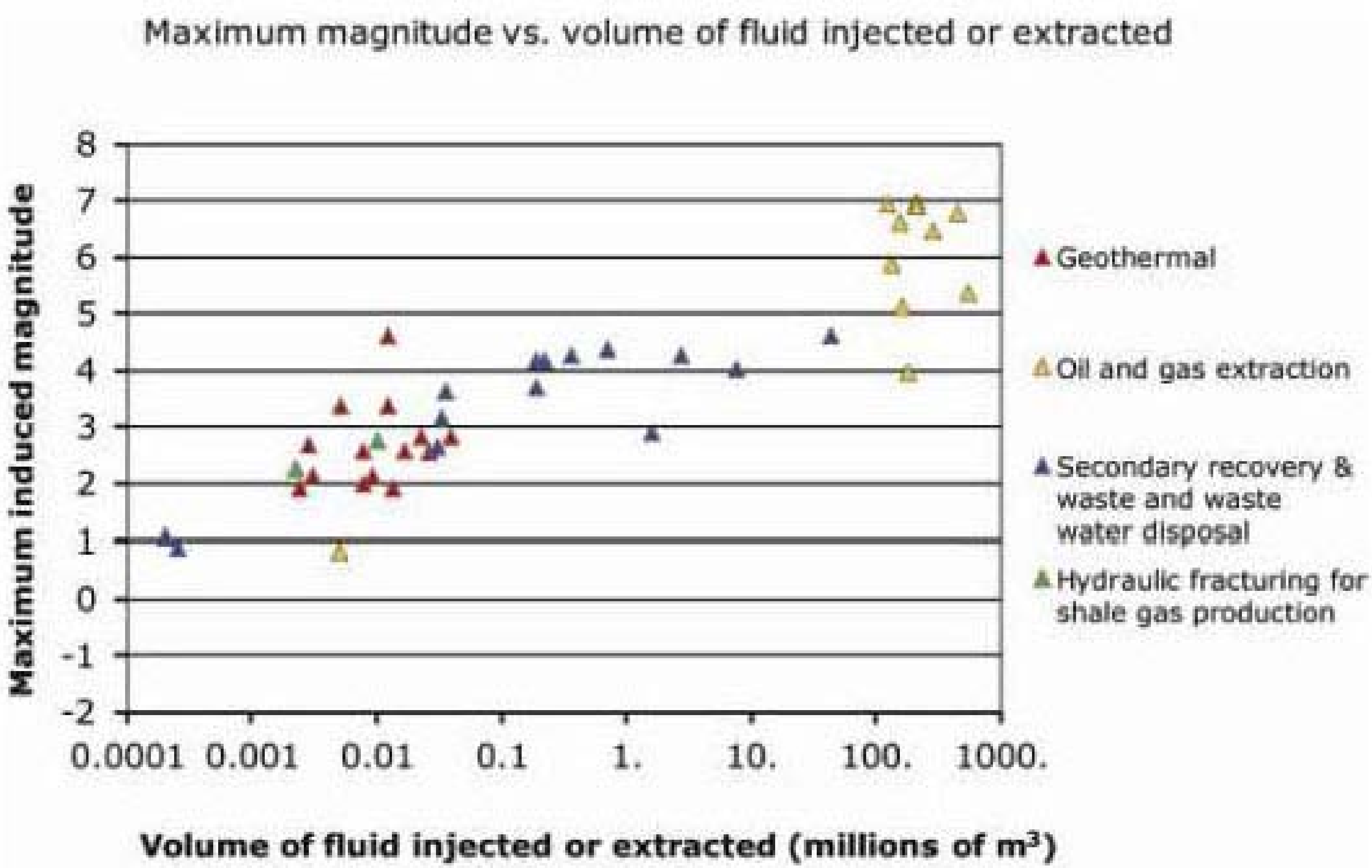
The factors important for understanding the potential to generate felt seismic events are complex and interrelated and include:

- the rate of injection or extraction
- volume and temperature of injected or extracted fluids
- pore pressure
- permeability of the relevant geologic layers
- faults, fault properties, fault location
- crustal stress conditions
- the distance from the injection point
- the length of time over which injection and/or withdrawal takes place

Energy Technology Potential for Induced Seismicity — Summary Points

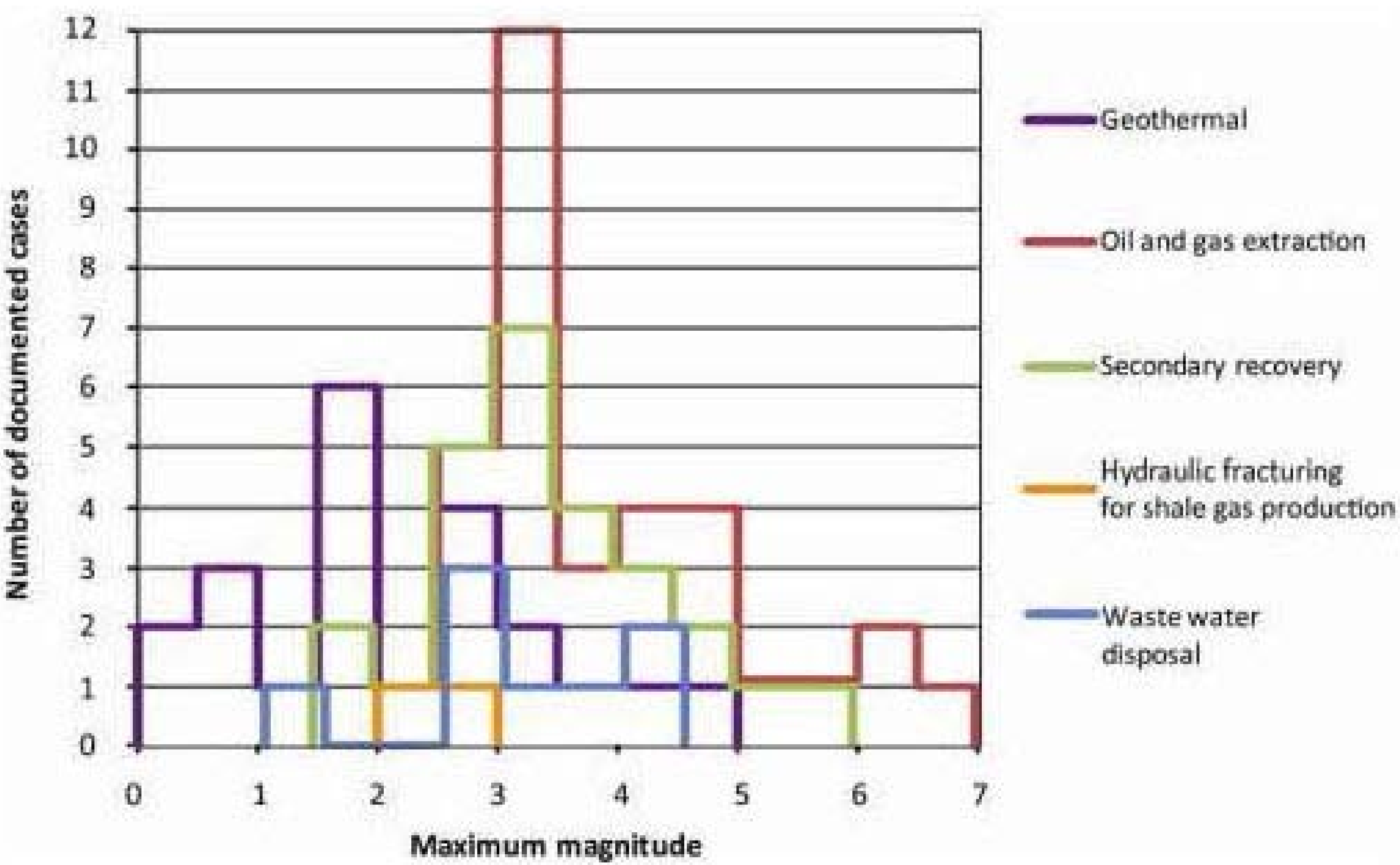
- The net fluid balance (*total balance of fluid introduced and removed*) appears to have the most direct consequence on changing pore pressure in the subsurface over time.

- Energy technology projects designed to maintain a balance between the amount of fluid being injected and the amount of fluid being withdrawn, such as geothermal and most oil and gas development, may produce fewer induced seismic events than technologies that do not maintain fluid balance.



Source: NRC (2012)

Histogram of projects by maximum induced magnitude



Source: NRC (2012)

Study Findings on Induced Seismicity Potential of Different Energy Technologies

- Geothermal
- Conventional oil & gas production
- Unconventional oil & gas production (shale gas)
- Energy waste water disposal
- Carbon capture and sequestration

Induced Seismicity Potential — Geothermal

- Induced seismicity appears related to both net fluid balance considerations and temperature changes produced in the subsurface

- Different forms of geothermal resource development appear to have differing potential for producing felt seismic events:

  - High-pressure hydraulic fracturing undertaken in some geothermal projects (EGS) has caused seismic events that are large enough to be felt

  - Temperature changes associated with geothermal development of hydrothermal resources has also induced felt seismicity (The Geysers)

Induced Seismicity Potential — Conventional Oil & Gas Production

- Generally, withdrawal associated with conventional oil and gas recovery has not caused significant seismic events, however several major earthquakes have been associated with conventional oil and gas withdrawal.

- Relative to the large number of waterflood projects for secondary recovery, the small number of documented instances of felt induced seismicity suggests such projects pose small risk for events that would be of concern to the public.

- The committee did not identify any documented, felt induced seismic events associated with EOR (tertiary recovery); the potential for induced seismicity is low.

Induced Seismicity Potential — Unconventional Oil & Gas Production (Shale Gas)

- The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events.

- ~35,000 wells have been hydraulically fractured for shale gas development to date in the United States.

- Only one case of demonstrated induced seismicity from hydraulic fracturing for shale gas has been documented worldwide (Blackpool, England – 2011).

Induced Seismicity Potential — Energy Waste Water Disposal

- The US currently has approximately 30,000 Class II waste water disposal wells (water from energy production). Very few felt induced seismic events reported as either caused by or likely related to these wells. Rare cases of waste water injection have produced seismic events, typically less than **M** 5.0.

- High injection volumes may increase pore pressure and in proximity to existing faults could lead to an induced seismic event.

- The area of potential influence from injection wells may extend over several square miles.

- Induced seismicity may continue for months to years after injection ceases.

- Evaluating the potential for induced seismicity in the location and design of injection wells is difficult because there are no cost-effective ways to locate faults and measure in situ stress.

Induced Seismicity Potential — Carbon Capture and Sequestration (CCS)

- The only long-term (~14 years) commercial CO_2 sequestration project in the world at the Sleipner field offshore Norway is small scale relative to commercial projects proposed in the US. Extensive seismic monitoring has not indicated any significant induced seismicity.

- There is no experience with the proposed injection volumes of liquid CO_2 in large-scale sequestration projects (> 1 million metric tonnes per year). If the reservoirs behave in a similar manner to oil and gas fields, these large volumes have the potential to increase the pore pressure over large areas and may have the potential to cause significant seismic events.

- CO_2 has the potential to react with the host/adjacent rock and cause mineral precipitation or dissolution. The effects of these reactions on potential seismic events are not understood.

Government Roles and Responsibilities (Findings)

1. Responsibility for oversight of activities that can cause induced seismicity is dispersed among a number of federal and state agencies.

2. Recent, potentially induced seismic events in the US have been addressed in a variety of manners involving local, state, and federal agencies, and research institutions. These agencies and research institutions may not have resources to address unexpected events; more events could stress this ad hoc system.

3. Currently the EPA has primary regulatory responsibility for fluid injection under the Safe Drinking Water Act; ***this act does not address induced seismicity***.

4. The USGS has the capability and expertise to address monitoring and research associated with induced seismic events. However, their mission does not focus on induced events. Significant new resources would be required if their mission is expanded to include comprehensive monitoring and research on induced seismicity.

Government Roles and Responsibilities (Gap & Proposed Actions)

Gap

Mechanisms are lacking for efficient coordination of governmental agency response to induced seismic events.

Proposed Actions

1. In order to move beyond the current ad hoc approach for responding to induced seismicity, relevant agencies including EPA, USGS, land management agencies, and possibly the Department of Energy, as well as state agencies with authority and relevant expertise, should consider developing coordination mechanisms to address induced seismic events that correlate to established best practices.

2. Appropriating authorities and agencies with potential responsibility for induced seismicity should consider resource allocations for responding to future induced seismic events.

Understanding Hazard and Risk to Manage Induced Seismicity (Finding)

Currently, methods do not exist to implement assessments of hazards upon which risk assessments depend. The types of information and data required to provide a robust hazard assessment include:

- Net pore pressures, in situ stresses, information on faults
- Background seismicity
- Gross statistics of induced seismicity and fluid injection for the proposed site activity

Understanding Hazard and Risk to Manage Induced Seismicity — Proposed Actions

1. A detailed methodology should be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The goals in developing the methodology would be to:
   - make assessments before operations begin in areas with a known history of felt seismicity
   - update assessments in response to observed induced seismicity

2. Data related to fluid injection (well locations coordinates, injection depths, injection volumes and pressures, time frames) should be collected by state and federal regulatory authorities in a common format and made accessible to the public (through a coordinating body such as the USGS).

3. In areas of high-density of structures and population, regulatory agencies should consider requiring that data to facilitate fault identification for hazard and risk analysis be collected and analyzed before energy operations are initiated.

Steps Toward Best Practices (Findings & Gap)

Findings

1. The DOE Protocol for EGS provides a reasonable initial model for dealing with induced seismicity that can serve as a template for other energy technologies.

2. Based on this model, two matrix-style protocols illustrate the manner in which activities can ideally be undertaken concurrently (rather than only sequentially), while also illustrating how these activities should be adjusted as a project progresses from early planning through operations to completion.

Gap

No best practices protocol for addressing induced seismicity is in place for each of these technologies, with the exception of the EGS protocol. The committee suggests that best practices protocols be adapted and tailored to each technology.

Study Research Recommendations

1. **Collecting field and laboratory data** on active seismic events possibly caused by energy development and on specific aspects of the rock system at energy development sites (for example, on fault and fracture properties and orientations, crustal stress, injection rates, fluid volumes and pressures).

2. **Developing instrumentation** to measure rock and fluid properties before and during energy development projects.

3. **Hazard and risk assessment** for individual energy projects.

4. **Developing models,** including codes that link geomechanical models with models for reservoir fluid flow and earthquake simulation.

5. **Conducting research on carbon capture and storage,** incorporating data from existing sites where carbon dioxide is injected for enhanced oil recovery, and developing models to estimate the potential magnitude of seismic events induced by the large-scale injection of carbon dioxide for storage.

Conclusion

Although induced seismic events have not resulted in loss of life or major damage in the United States, their effects have been felt locally, and they raise some concern about additional seismic activity and its consequences in areas where energy development is ongoing or planned.

Further research is required to better understand and address the potential risks associated with induced seismicity.

Committee membership

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Jason Ortego, Research Associate
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Disposal of Hydrofracking-Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquakes

Scott M. Ausbrooks, The Arkansas Geological Survey

Steve Horton, Ph.D., CERI at University of Memphis

Contributors:

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D. Steiner, and K. Tucker

USGS: NEIC locations and notification; two seismic stations

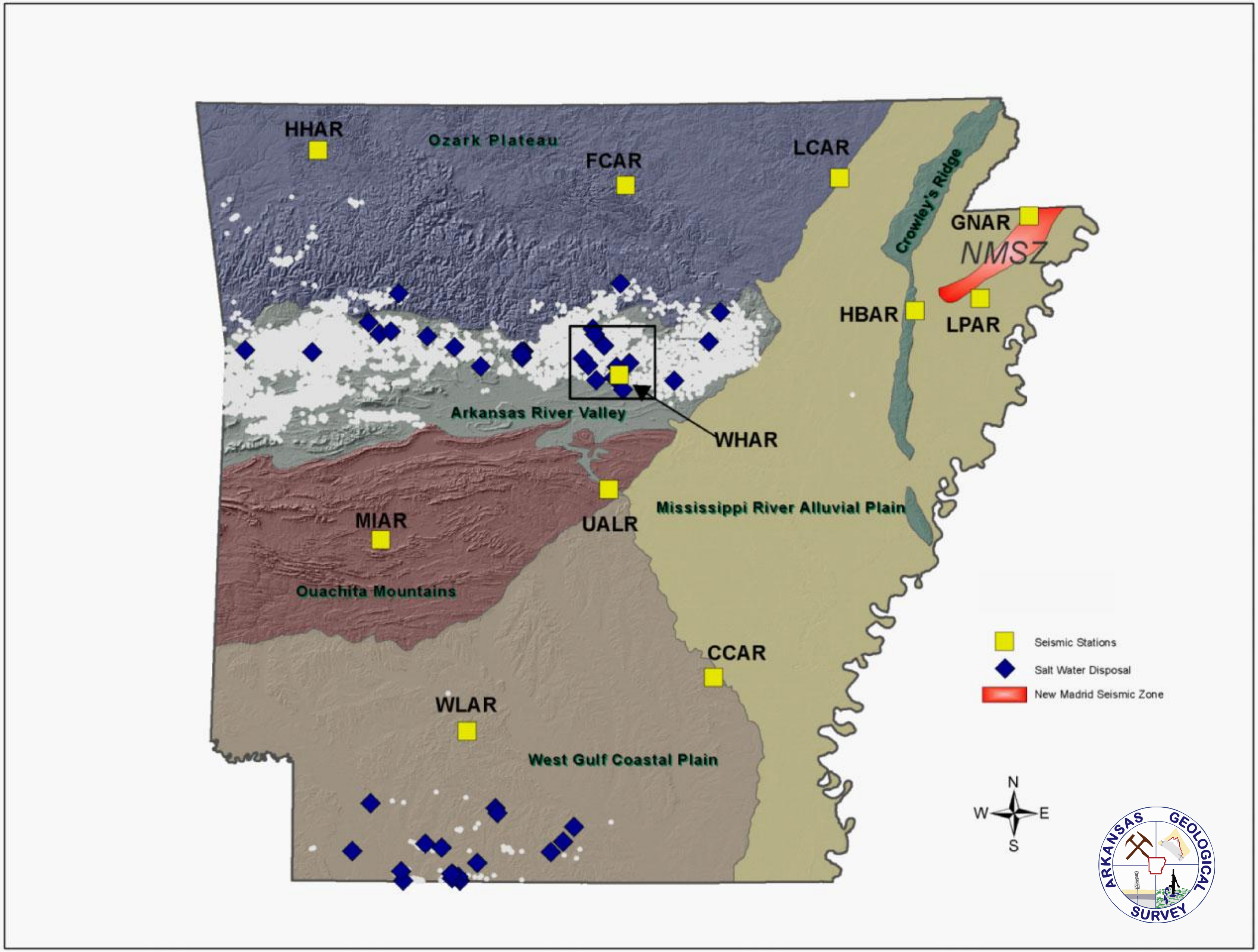
OVERVIEW

• The Guy-Greenbrier fault, a previously unknown fault, is illuminated by over a 1,300 earthquakes (**M≤4.7**) that occurred between September, 2010, and present.

• The fault is theoretically capable of producing a potentially damaging M5.6 – 6.0 earthquake.

• Two well-documented cases - Rocky Mountain Arsenal, Colorado, in the 1960s and Paradox Valley, Colorado, in the 1990s - demonstrate that fluid injection into the subsurface can trigger earthquakes.

• A plausible hydraulic connection exists between the injection depths at a waste-disposal well and the nearby Guy-Greenbrier Fault.



HHAR
Ozark Plateau
FCAR
LCAR
Crowley's Ridge
GNAR
NMSZ
HBAR
LPAR
Arkansas River Valley
WHAR
UALR
Mississippi River Alluvial Plain
MIAR
Ouachita Mountains
CCAR
WLAR
West Gulf Coastal Plain
Seismic Stations
Salt Water Disposal
New Madrid Seismic Zone
N
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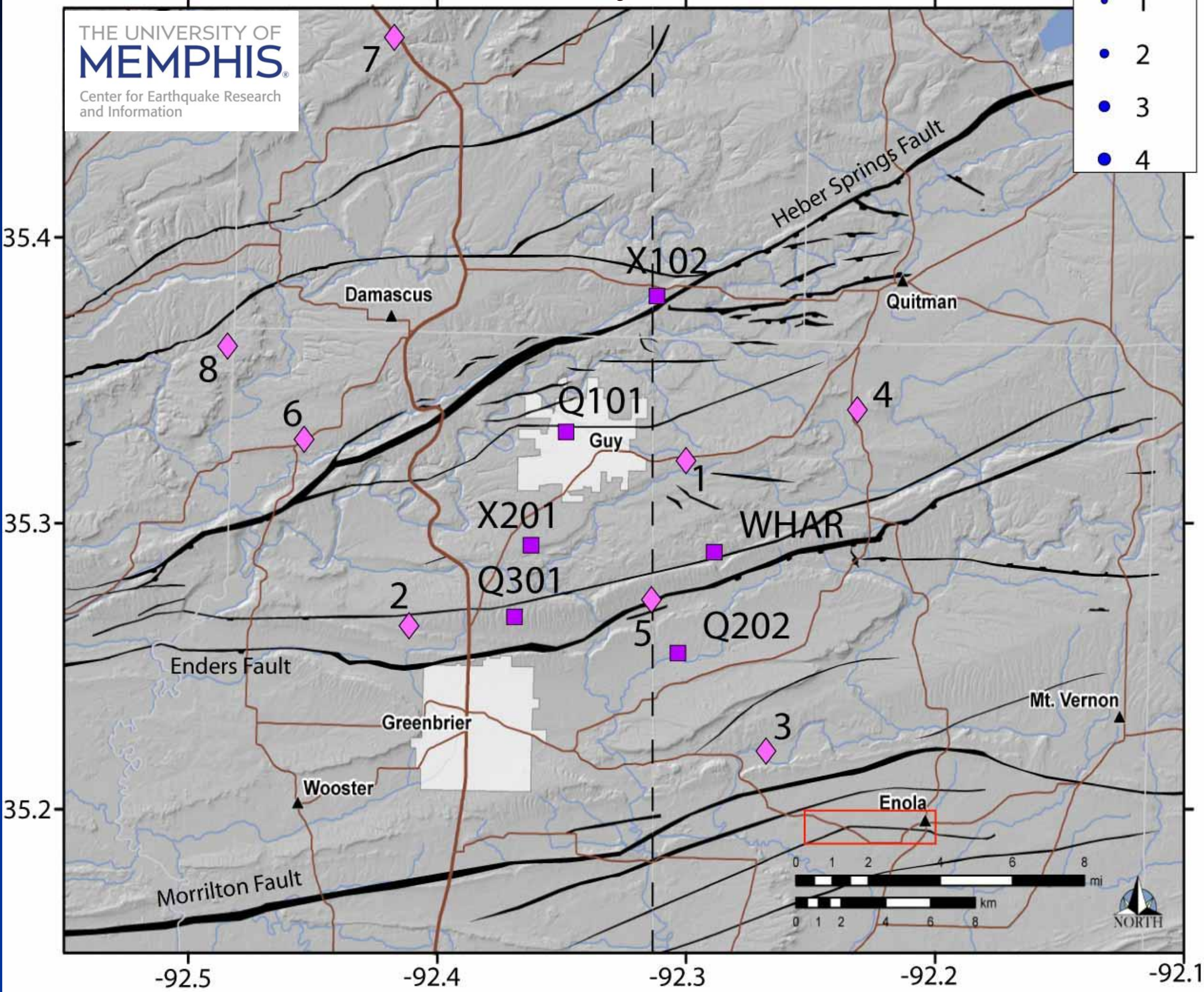
ARKANSAS GEOLOGICAL SURVEY

Study Area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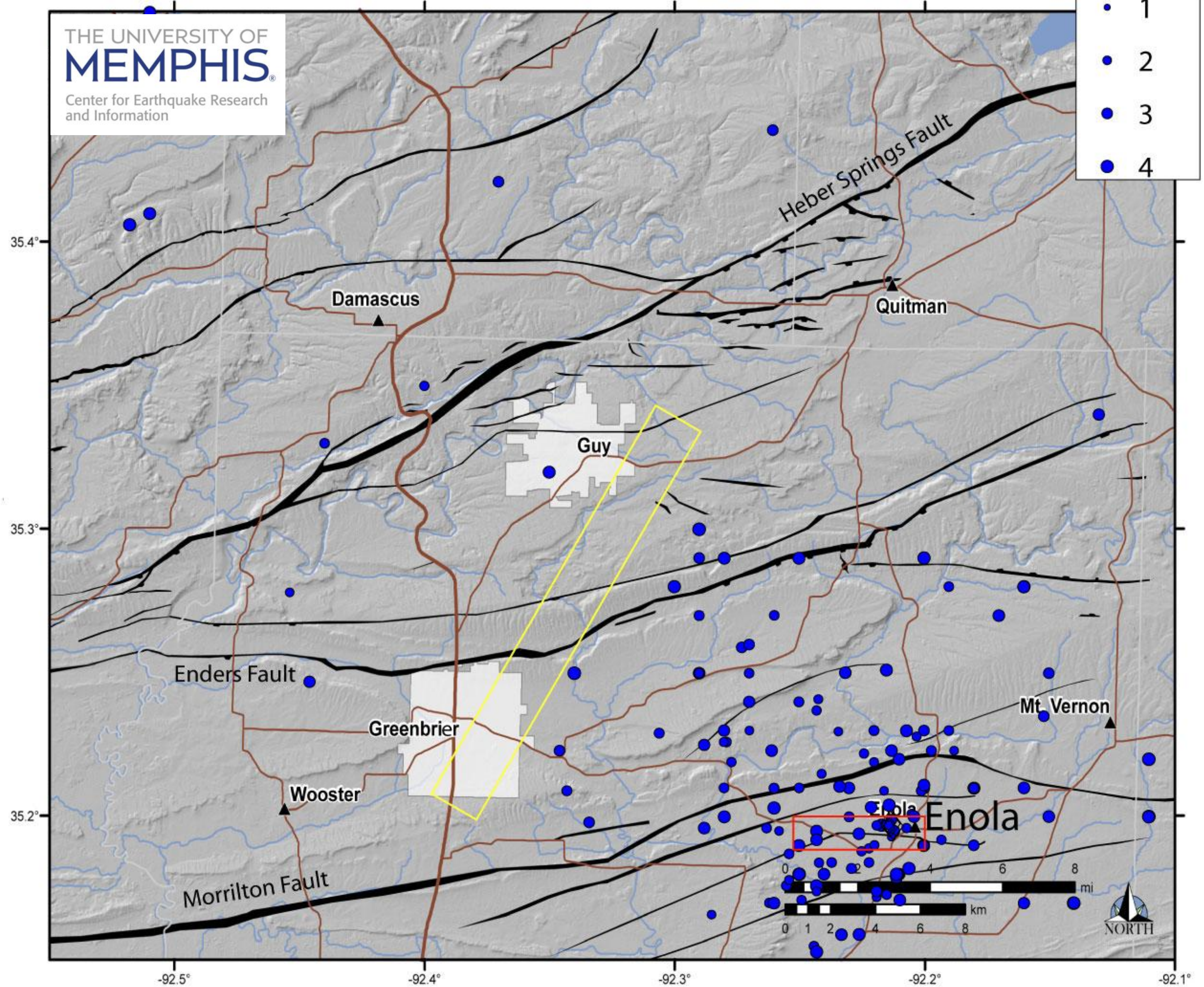
Center for Earthquake Research and Information
1
2
3
4
Heber Springs Fault
X102
Damascus
Quitman
8
7
6
Q101
Guy
4
1
X201
WHAR
Q301
2
5
Q202
Enders Fault
Greenbrier
3
Mt. Vernon
Wooster
Enola
Morrilton Fault
0 1 2 4 6 8 mi
0 1 2 4 6 8 km
NORTH
35.4
35.3
35.2
-92.5
-92.4
-92.3
-92.2
-92.1

1976 - 2008



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1
2
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4
Heber Springs Fault
Damascus
Quitman
Guy
Enders Fault
Greenbrier
Mt. Vernon
Wooster
Enola
Morrilton Fault
35.4°
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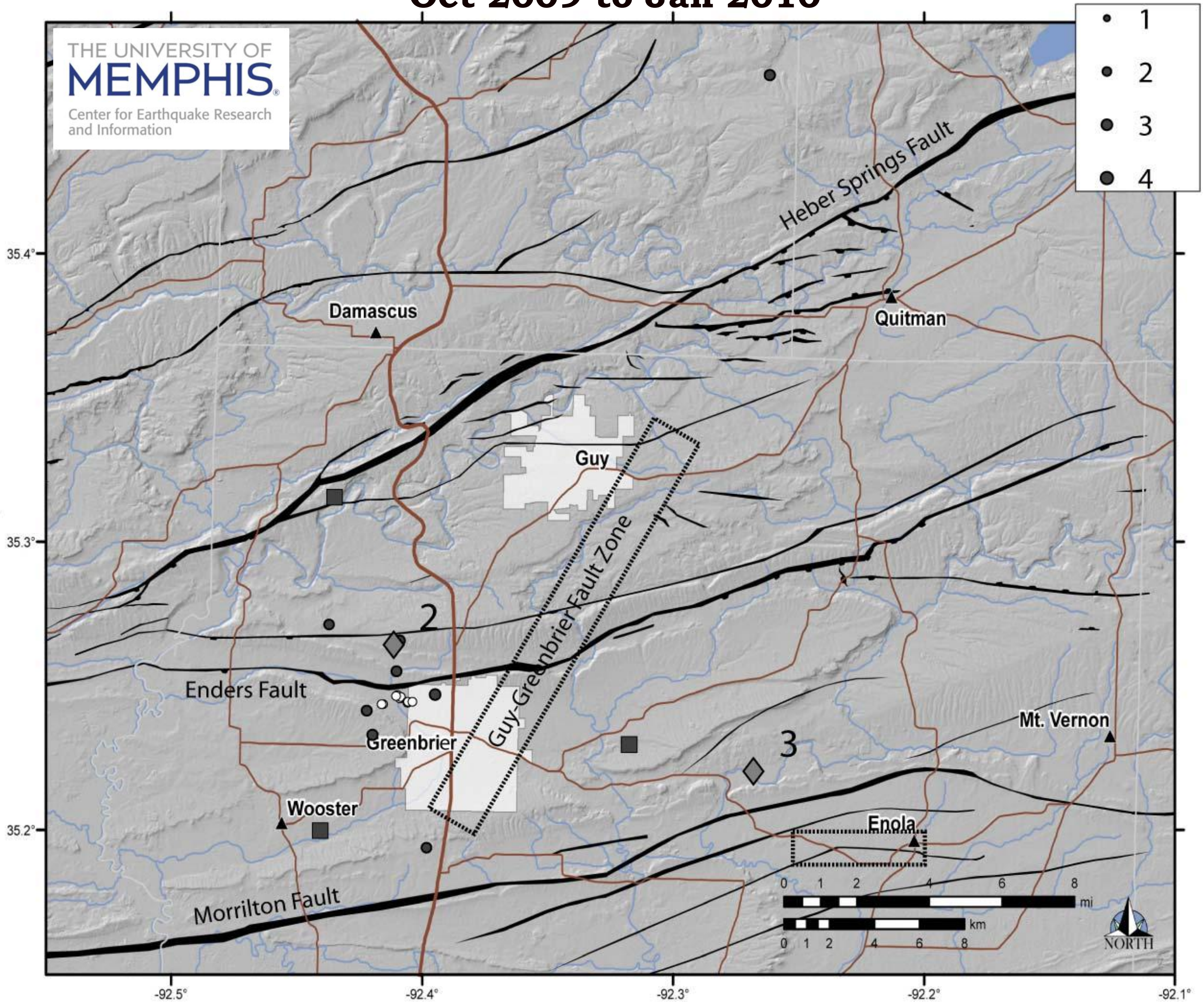
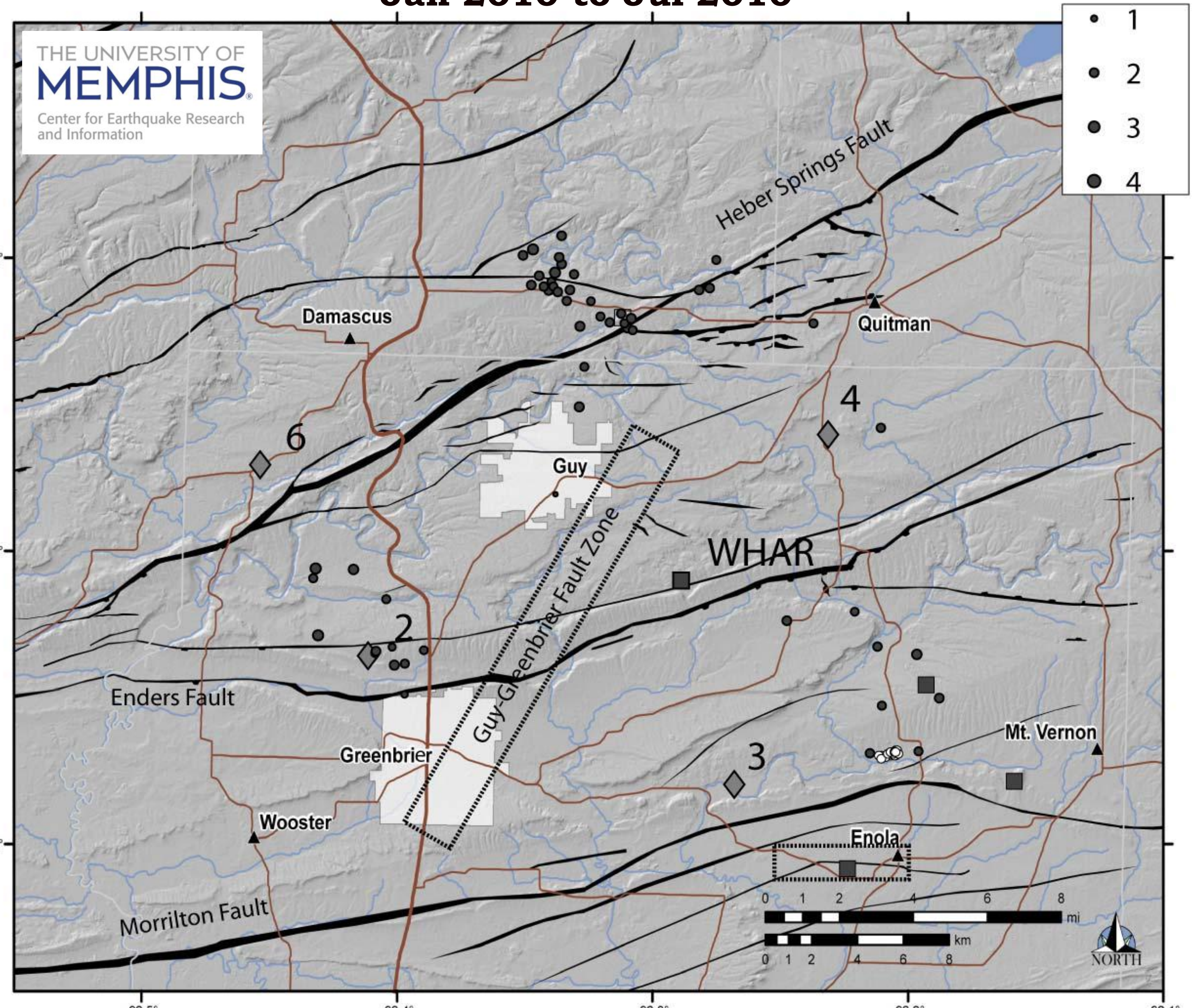
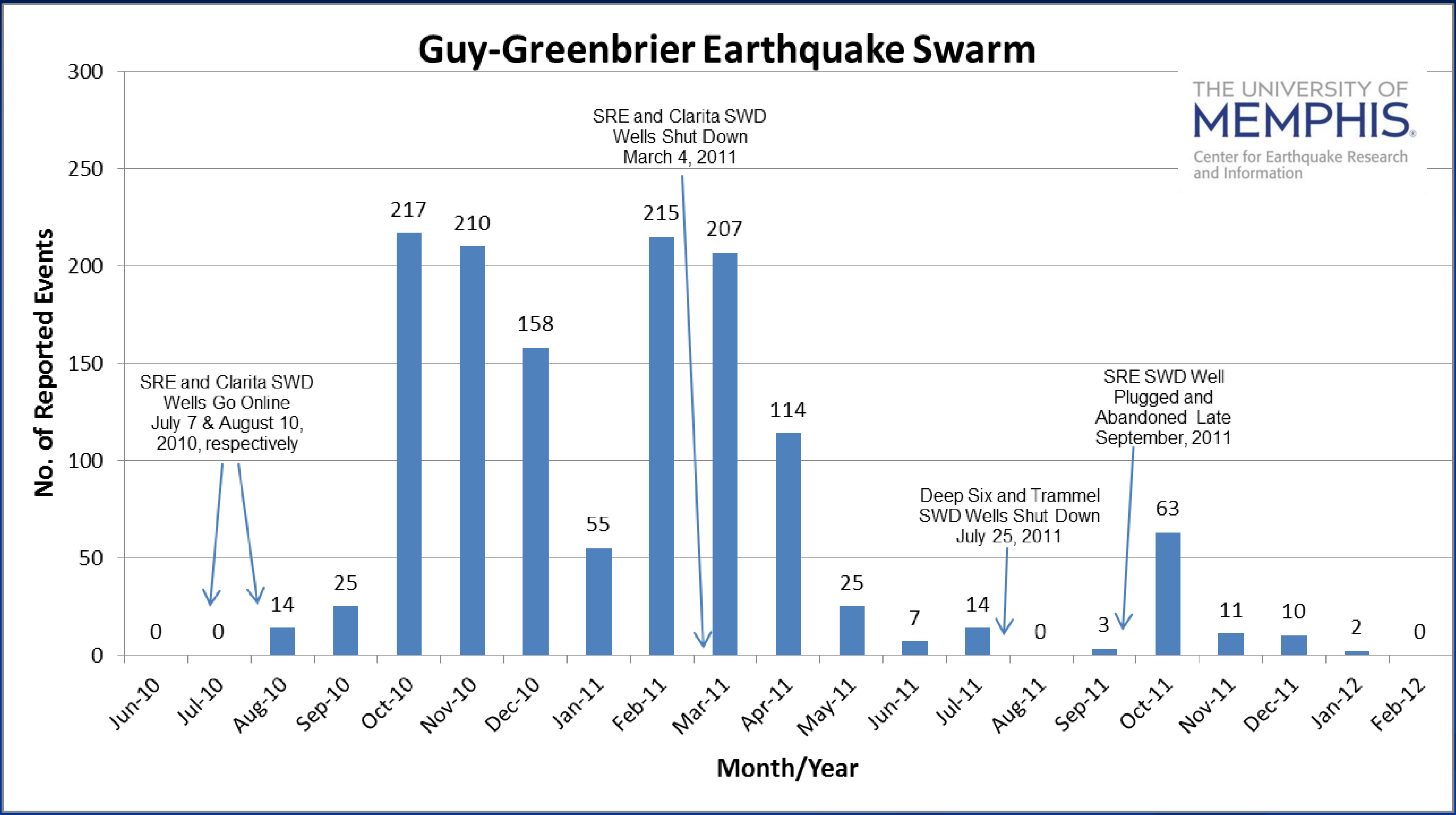
NORTH

Oct 2009 to Jan 2010



Jan 2010 to Jul 2010




Guy-Greenbrier Earthquake Swarm
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Center for Earthquake Research and Information
No. of Reported Events
300
250
200
150
100
50
0
SRE and Clarita SWD Wells Go Online July 7 & August 10, 2010, respectively
SRE and Clarita SWD Wells Shut Down March 4, 2011
Deep Six and Trammel SWD Wells Shut Down July 25, 2011
SRE SWD Well Plugged and Abandoned Late September, 2011
0
0
14
25
217
210
158
55
215
207
114
25
7
14
0
3
63
11
10
2
0
Jun-10
Jul-10
Aug-10
Sep-10
Oct-10
Nov-10
Dec-10
Jan-11
Feb-11
Mar-11
Apr-11
May-11
Jun-11
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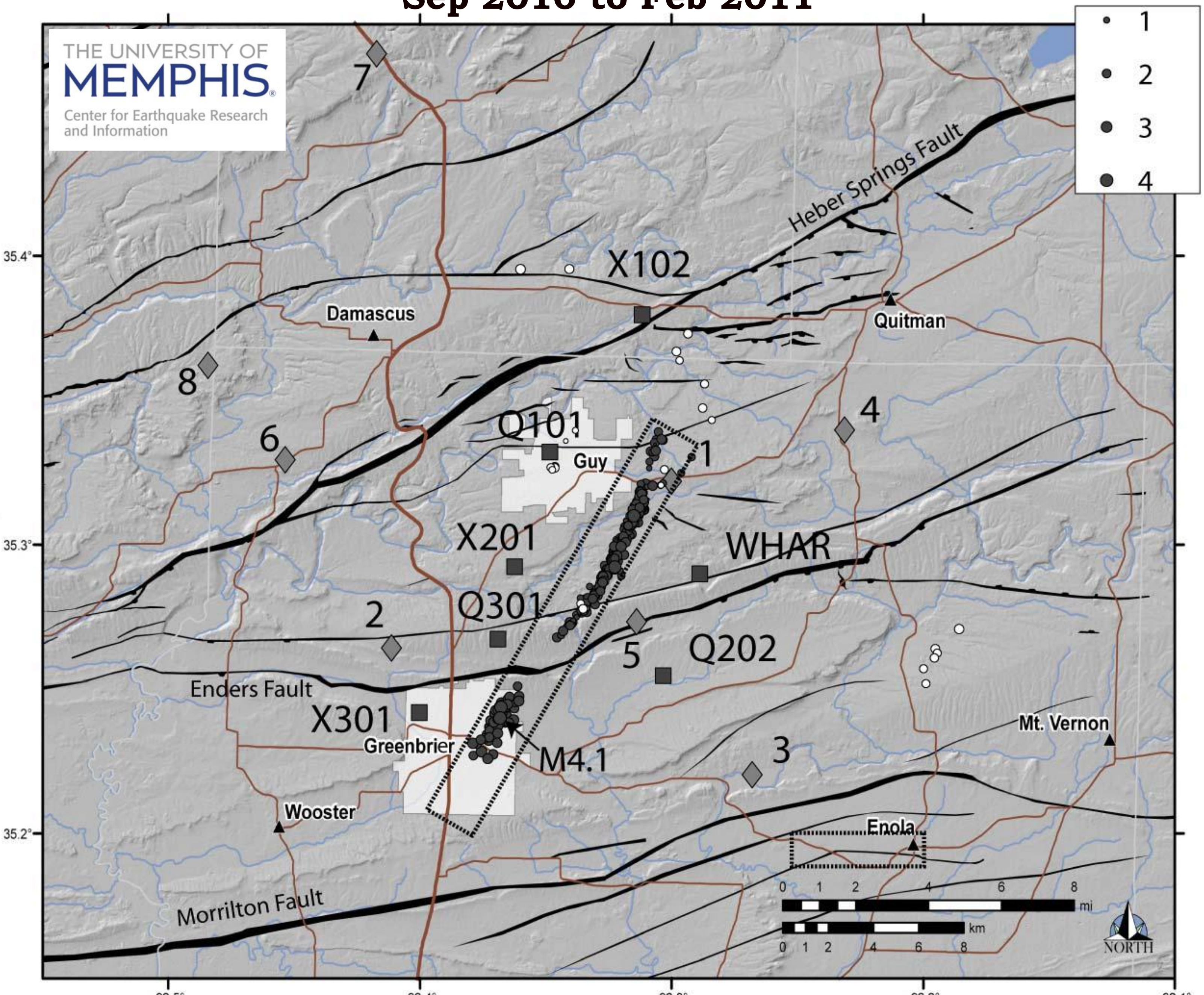
Sep-11
Oct-11
Nov-11
Dec-11
Jan-12
Feb-12
Month/Year

Sep 2010 to Feb 2011

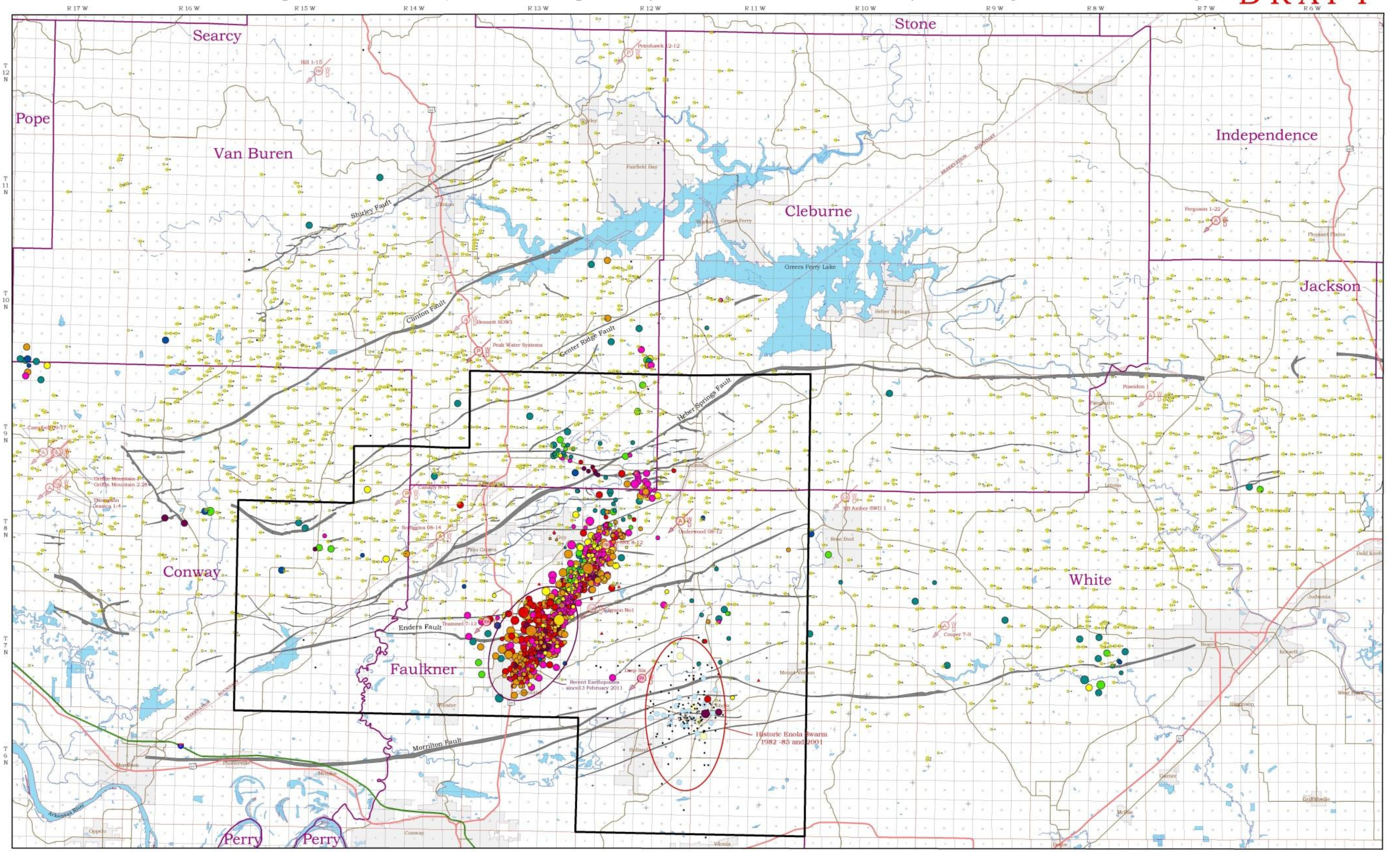


Arkansas Geological Survey
Bekki White, Director and State Geologist

Compilation of USGS/CERI Earthquakes (December 2008 to Present) in the Fayetteville Shale Play

GH-EQ-USGS-CERI-EVENTS-001

DRAFT



Earthquake Symbols

Depth	Magnitude
<1.9 km	<0.0
2.0-2.9 km	0.0-0.9
3.0-3.9 km	1.0-1.9
4.0-4.9 km	2.0-2.9
5.0-5.9 km	3.0-3.9
6.0-6.9 km	4.0-4.9
7.0-7.9 km	
>8.0 km	

Historic Earthquakes

Magnitude

- 0.0 - 1.9
- 2.0 - 2.9
- 3.0 - 3.9
- 4.0 - 4.9

Disposal Wells

- Expired
- Active
- Permitted
- Plugged & Abandoned

Gas Wells

- Permitted Well
- Producing
- Recently Completed
- Dry and Abandoned
- Plugged
- Shut In

Map Symbols

- Interstate
- US HWY
- State HWY
- AOGC Moratorium Area
- Counties
- AOGC_AGS_Faults *(Fault thickness depicts amount of displacement)*

Scale

2 1 0 2 4 6 8 10 12 Miles

2 1 0 2 4 6 8 10 12 14 16 18 20 Kilometers

About the Map

The subsurface faults depicted on this map are based on available fault data on file at the Arkansas Geological Survey (AGS) and the Arkansas Oil and Gas Commission (AOGC). Faults provided by the AOGC were compiled from integration dockets prepared by various geologists of the companies operating in the Fayetteville Shale Gas Play. These faults are for illustration purposes only and may not represent all faults in a given location or the origin of the earthquakes depicted on this map.

Sources

Earthquake data was acquired online from the USGS/Center for Earthquake Research and Information (CERI) at *http://www.ceri.memphis.edu.*

Faults provided by the AOGC were compiled from integration dockets prepared by various geologists of the companies operating in the Fayetteville Shale Gas Play. *http://www.aogc.state.ar.us*

County Boundary (vector digital data). 2011. Arkansas Highway and Transportation Department, AHTD, Little Rock, AR, Available Online: *http://www.geostor.arkansas.gov/G6/Home.html?id=a2c188917604e51a3431fc20765de451, http://www.geostor.arkansas.gov*

Highway (vector digital data). 2011. Arkansas Highway and Transportation Department, Little Rock, AR. *http://www.geostor.arkansas.gov/G6/Home.html?id=dc2912e4d02132440f90072737d569b6,http://www.geostor.arkansas.gov*

High Resolution: National Hydrography Dataset Waterbody Feature (vector digital data). 2009. U.S. Geological Survey in cooperation with U.S. Environmental Protection Agency, USDA Forest Service, and other Federal, State and local partners (see dataset specific metadata under Data_Set_Credit for details). Available: *http://www.geostor.arkansas.gov/G6/Home.html?id=4c9294b5325f5ad19127e9468406db2a, http://www.geostor.arkansas.gov*

Arkansas

Disclaimer

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Arkansas Geological Survey.

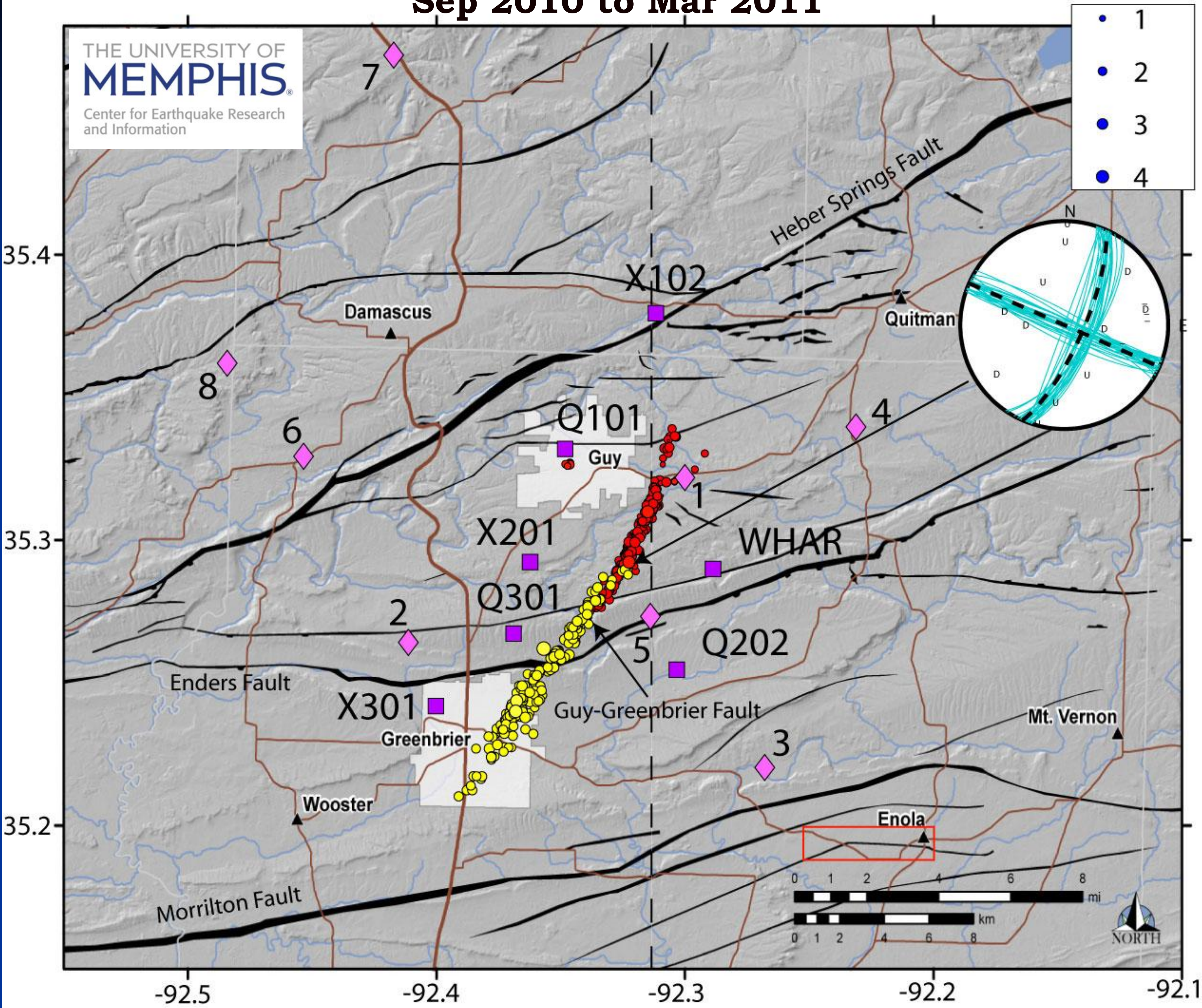
Scott M. Ausbrooks
David H. Johnston
2011

1 : 100,000

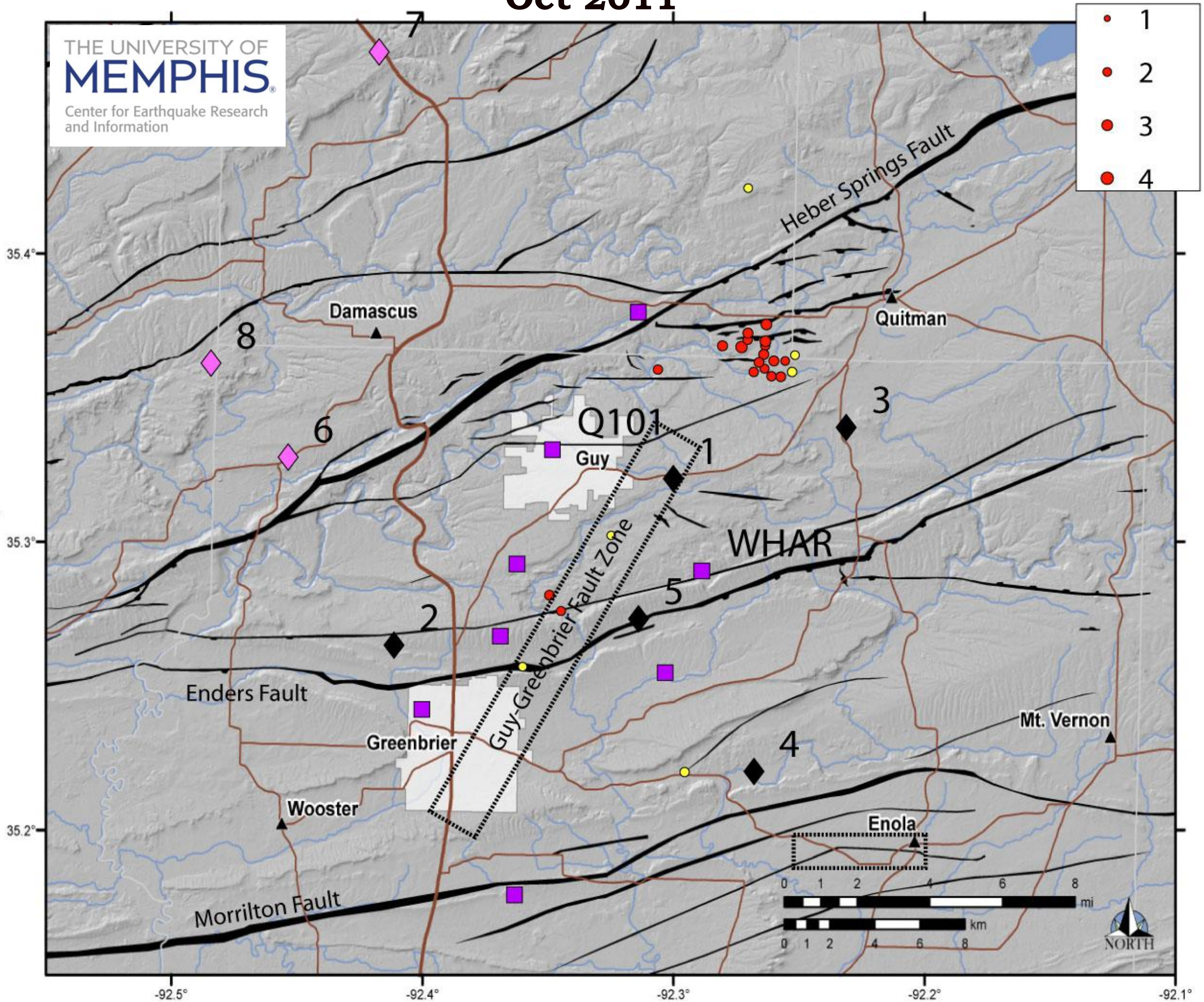
Jerry W. Clark

Revised: 11 October 2011

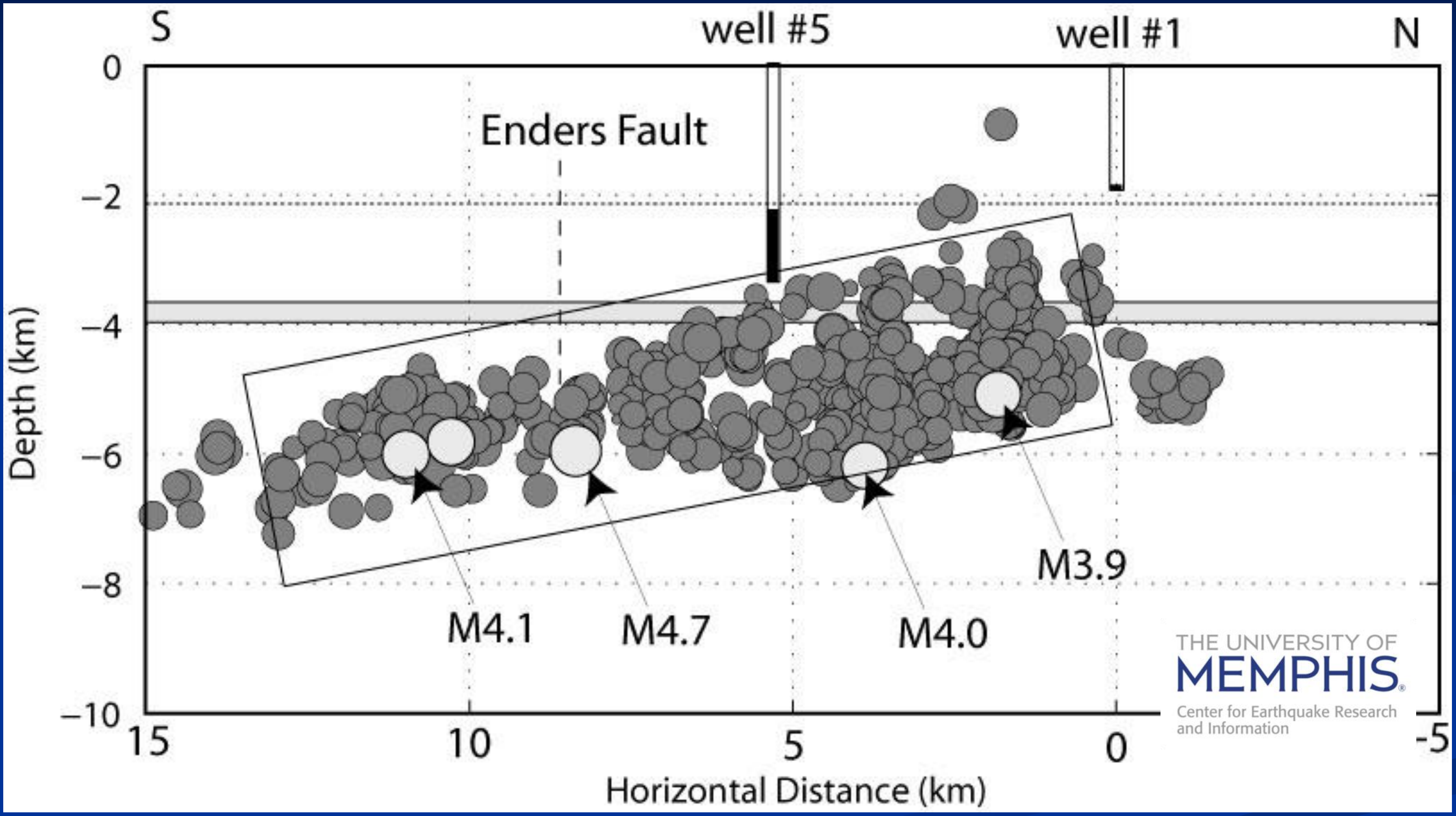
Sep 2010 to Mar 2011



Oct 2011



THE UNIVERSITY OF MEMPHIS
Center for Earthquake Research and Information
1
2
3
4
Heber Springs Fault
Damascus
Quitman
Q101
Guy
WHAR
Guy-Greenbrier Fault Zone
Enders Fault
Greenbrier
Wooster
Mt. Vernon
Enola
Morrilton Fault
1
2
3
4
5
6
7
8
35.4°
35.3°
35.2°
-92.5°
-92.4°
-92.3°
-92.2°
-92.1°
0 1 2 4 6 8 mi
0 1 2 4 6 8 km
NORTH



S
well #5
well #1
N
Enders Fault
Depth (km)
0
−2
−4
−6
−8
−10
M4.1
M4.7
M4.0
M3.9
15
10
5
0
-5
Horizontal Distance (km)
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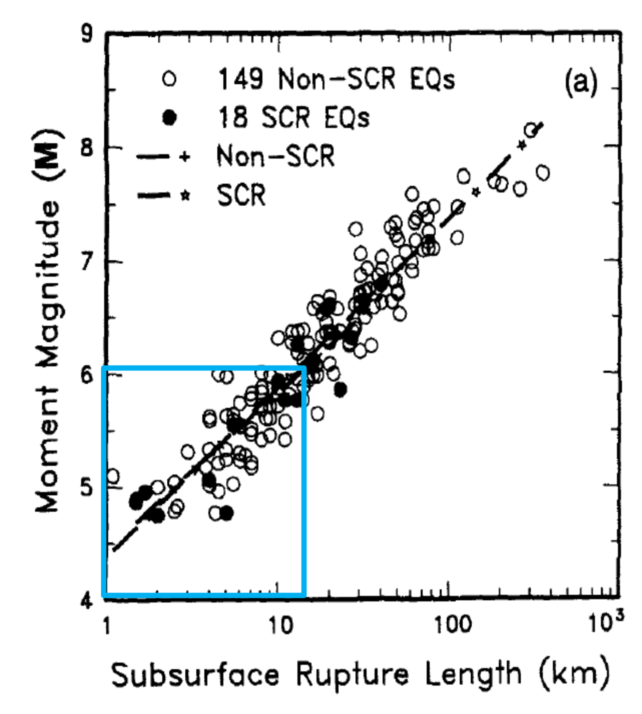
How large of earthquake can occur on the Guy-Greenbrier fault?

M0=uAd ~ M
Area = Length x Width ~ 13x3.2 = 41km^2
Length=12km

Wells and Coppersmith (1994)
M=3.98 + 1.02log(area)
M(24)=5.4
M(41)=5.6

M=4.33+1.49log(RLD)
M(6)= 5.5
M(13)=6.0



Fault capable of M 5.6 – 6.0 earthquake if it ruptures as single event.

How much strain energy has already been used?

5.6 ≤ **M** ≤ 6.0 => 2.82e24 ≤ M_0 ≤ 1.122e25 dyne-cm

cumulative seismic moment to date
~2.39e+23 dyne-cm => ~**M**4.88 earthquake.

The remaining seismic moment,
2.5792e24 ≤ M_0 ≤ 1.0981e25 dyne-cm => **M**5.57 – 5.99

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What is the mechanism for triggering earthquakes by injection of fluids?

The mechanism by which fluid injection triggered the earthquakes is the reduction frictional resistance to faulting, a reduction which occurs with increase in pore pressure (Healy et al., 1968).

The implication of the pore-pressure mechanism *is* that the rocks were stressed to near their breaking strength before the injection of fluid (Healy et al., 1968).

In the presence of pore fluids, the condition for slip on a fault is

$$|\sigma_s| = S_0 + \mu(\sigma_n - P)$$

where σ_s is the shear stress, S_0 is the cohesion of the surface, μ is the coefficient of friction, σ_n is the normal stress, and P is pore pressure.

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What is the Comparison between the Rocky Mountain Arsenal SWD and the SWD's associated with Guy-Greenbrier EQ Swarm?

27 September 1968, Volume 161, Number 3848

SCIENCE

The Denver Earthquakes

Disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, Colorado.

J. H. Healy, W. W. Rubey, D. T. Griggs, C. B. Raleigh

In November 1965 David Evans (2), a consulting geologist in Denver, showed a correlation between the volumes of fluid injected into the well and the number of earthquakes detected at Bergen Park, and publicly suggested that a direct relation did exist (Fig. 1, right).

The proximity of the earthquakes to the Denver metropolitan area created considerable public interest and concern. A number of the larger earthquakes, of Richter magnitude between 3 and 4, were felt over a wide area, and minor damage was reported near the epicenters. The sudden appearance of seismic activity close to a major city

- Injection into crystalline basement rock 3.67 km below the surface.
- Most of the earthquakes were located about 5 km northwest of the disposal well at depths between 3 and 8 km (Herrmann, 1981).
- The largest event at the Arsenal, an **M 5.3,** occurred several kilometers from the injection well more than a year after injection ended.

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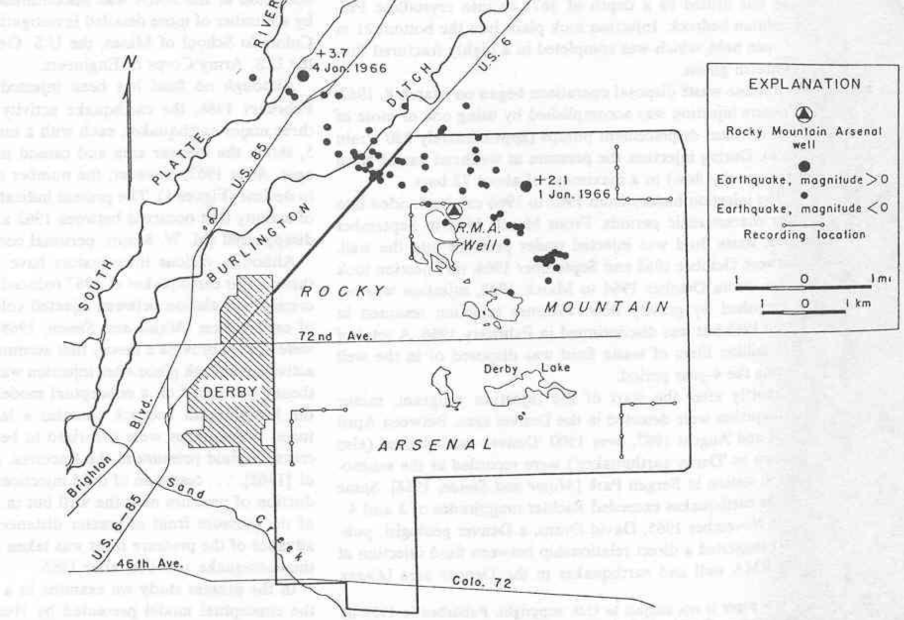


Fig. 2. Locations of earthquakes recorded from mobile microseismic stations during January and February 1966 [from *Healy et al.*, 1966].

HSIEH AND BREDEHOEFT: DENVER EARTHQUAKES

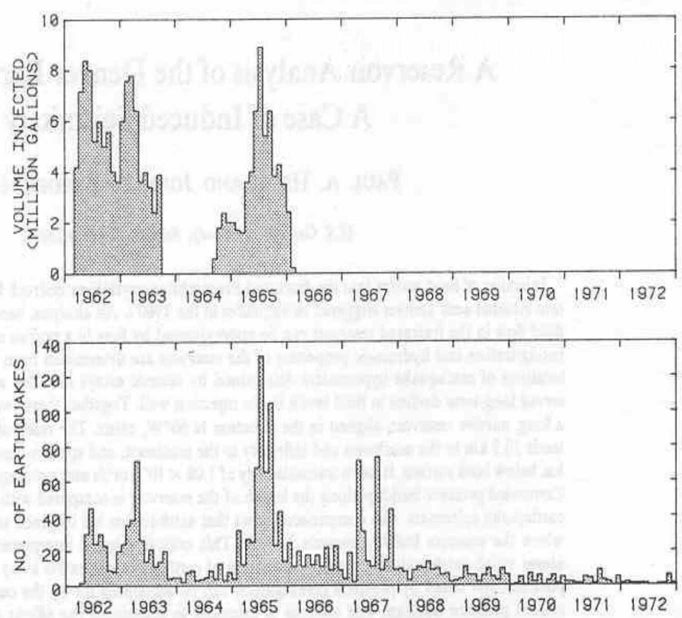


Fig. 1. Comparison of fluid injected and the frequency of earthquakes at the Rocky Mountain Arsenal. Upper graph shows monthly volume of fluid waste injected in the disposal well. Lower graph shows number of earthquakes per month. The apparent correlation for the period 1962–1966 was first noted by *Evans* [1966].

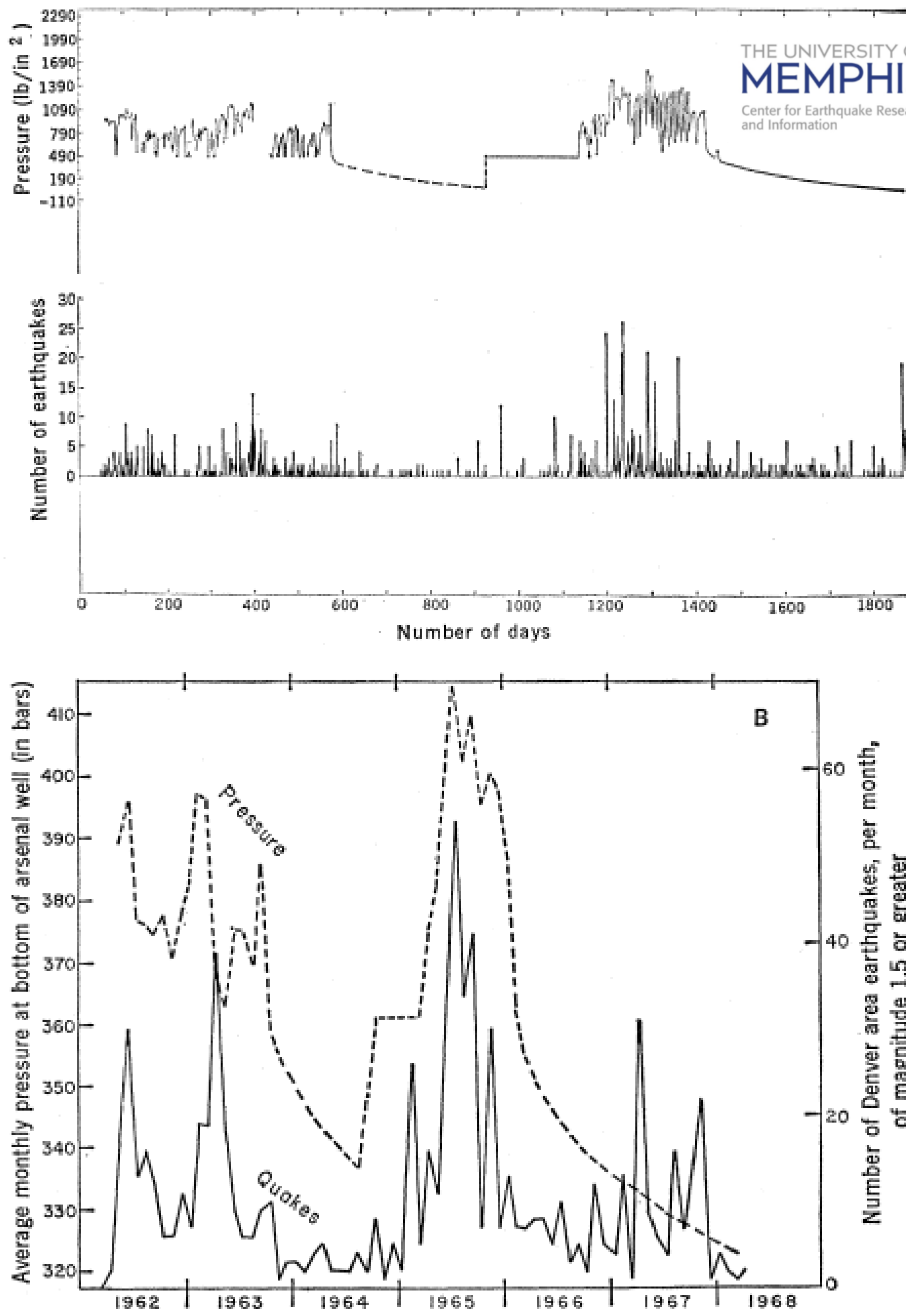
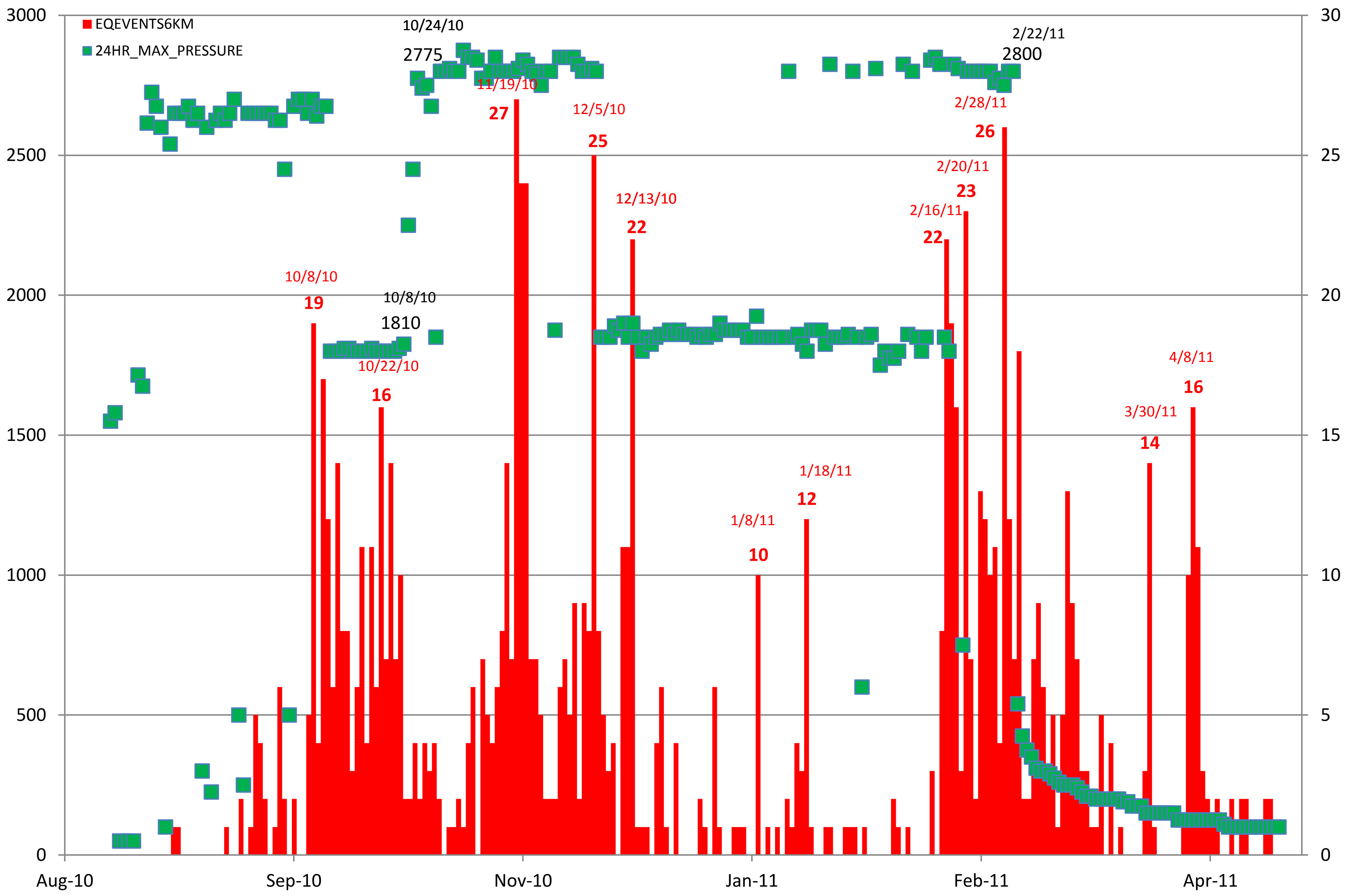
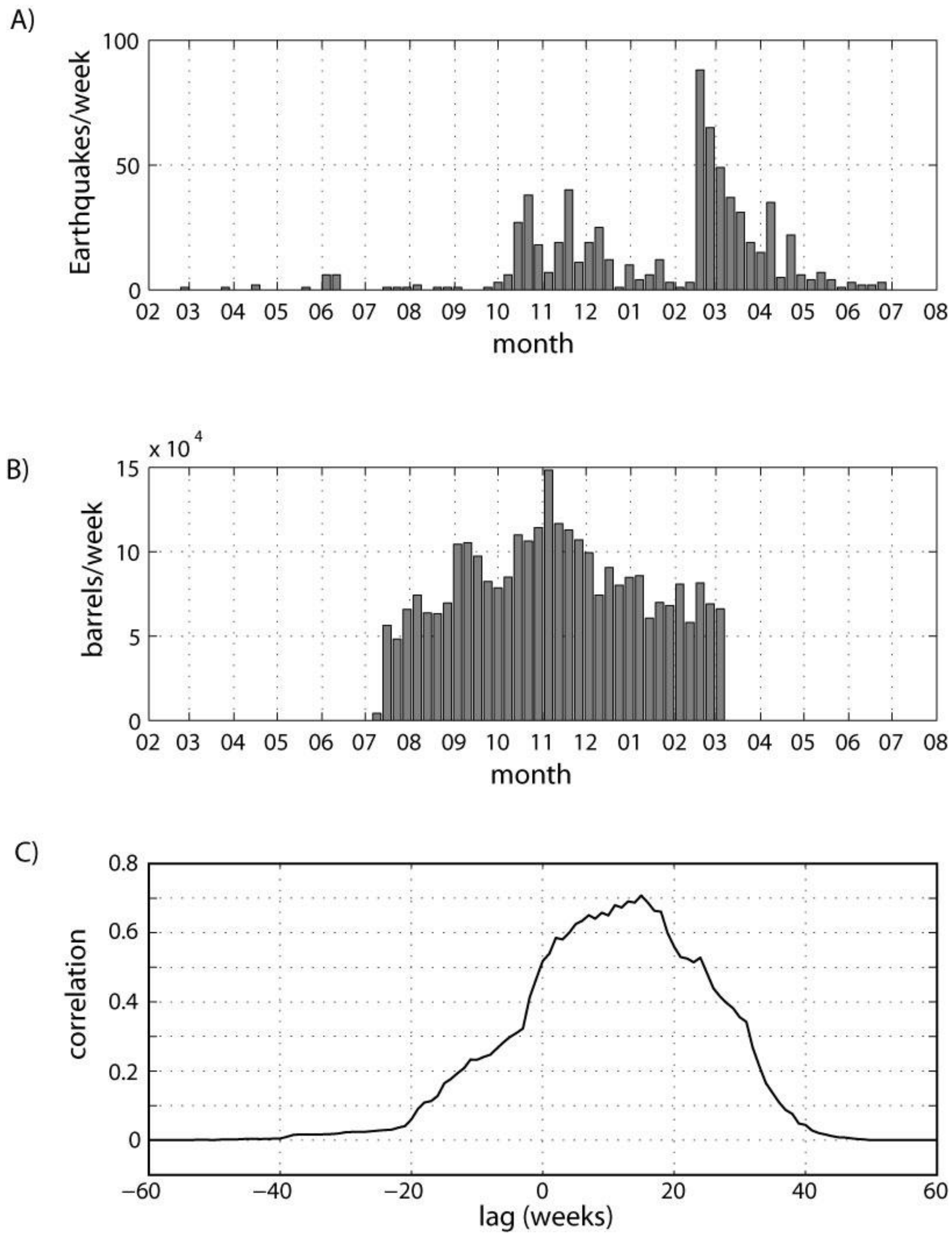


Fig. 7. (A) Daily pressure plotted relative to number of earthquakes. The dashed portions in the pressure curve are interpolated where only data on the volume of fluid injected were available. (B) Comparison of number of earthquakes and pressure, on a monthly basis.

Clarita Operating, LLC Wayne L. Edgmon SWD
8/18/2010-4/30/2011 - Daily Max Recorded TBG Pressures





Cross correlation of earthquake frequency and combined injection volume at well#1 and well#5.

A) Number of earthquake with m≥2.0 per week is plotted for the entire study area. The start time coincides with the completion of installation of the Arkansas seismic Network (see fig. 1) on February 26, 2010.

B) Combined injection volume at wells #1 and #5 per week. Injection at both wells ceased on March 3, 2011.

C) Normalized cross-correlation coefficient with peak 0.7 and lag of 15 weeks.

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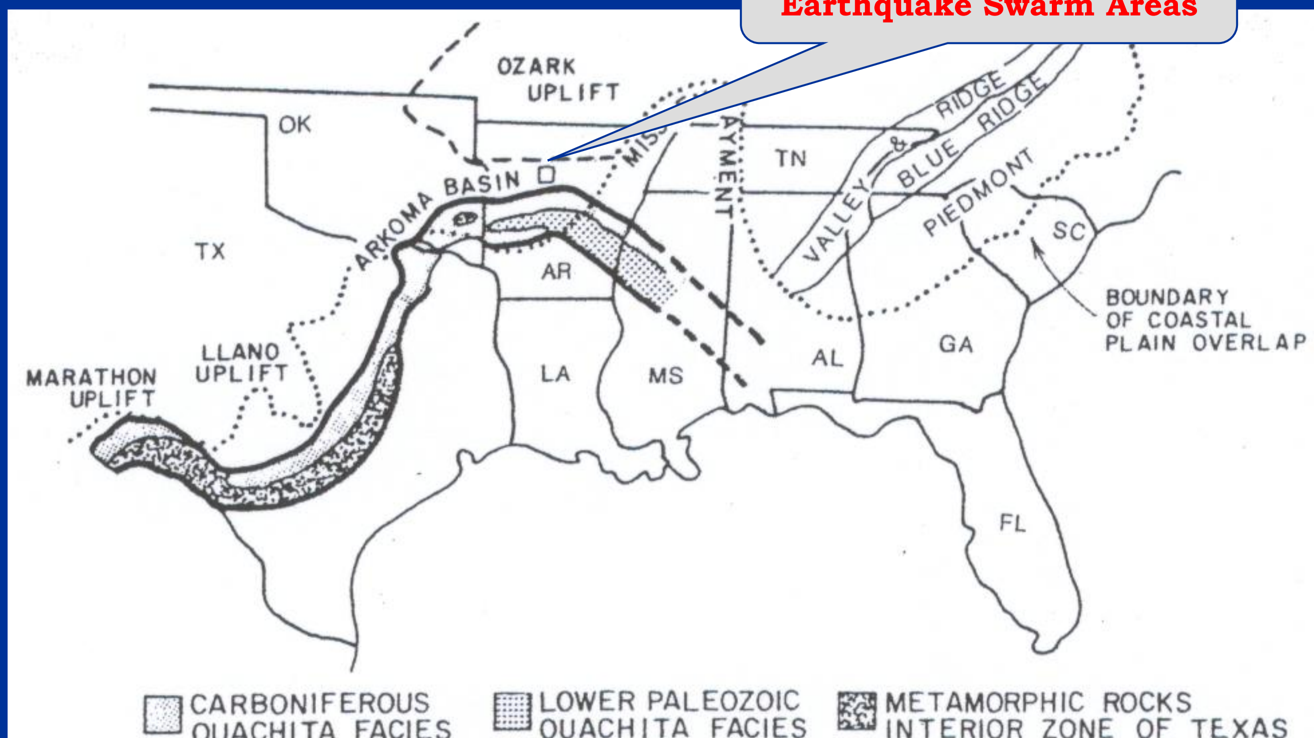
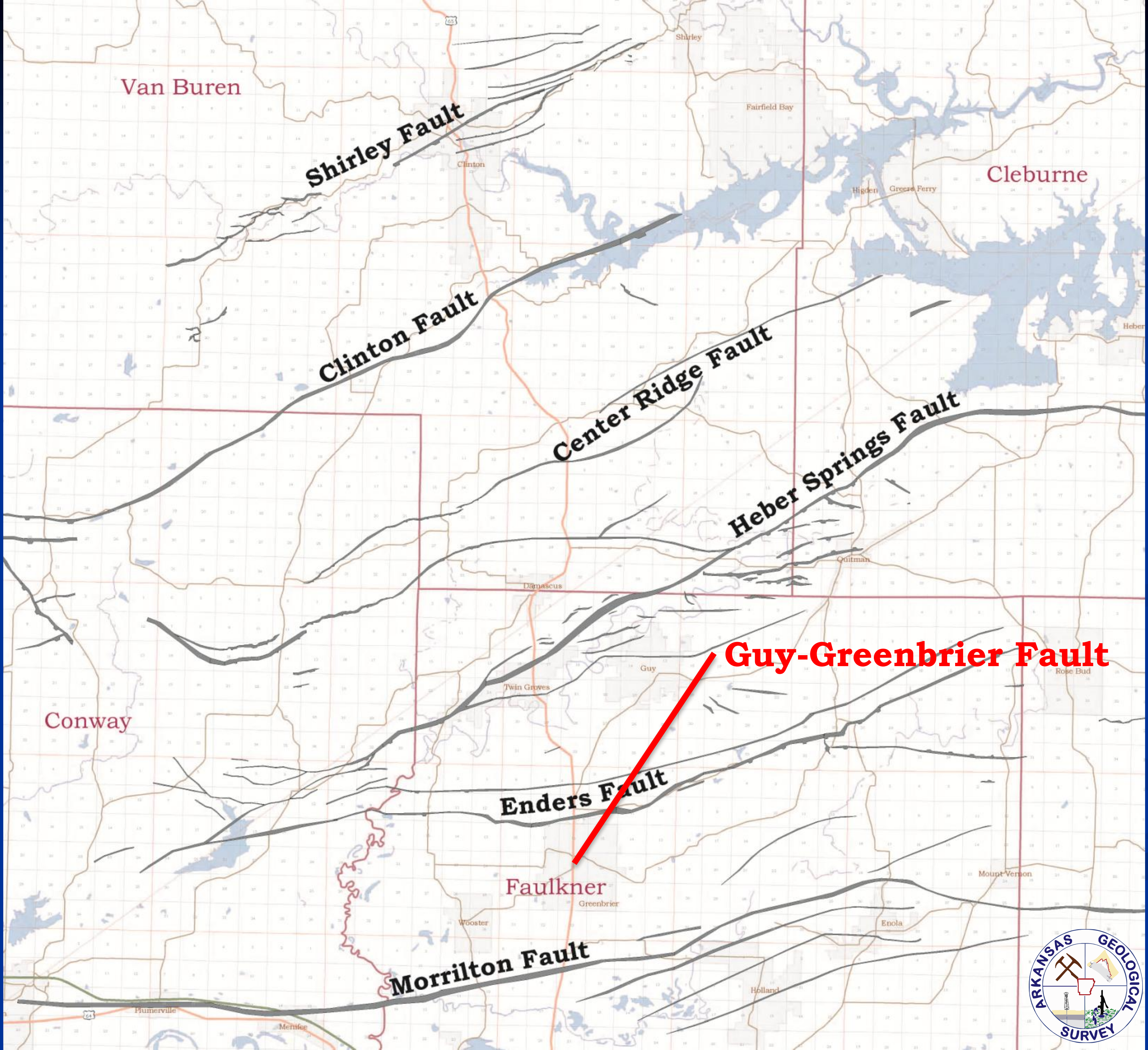
What is the plausible connection between the SWD wells and the earthquakes?

Geologic Setting

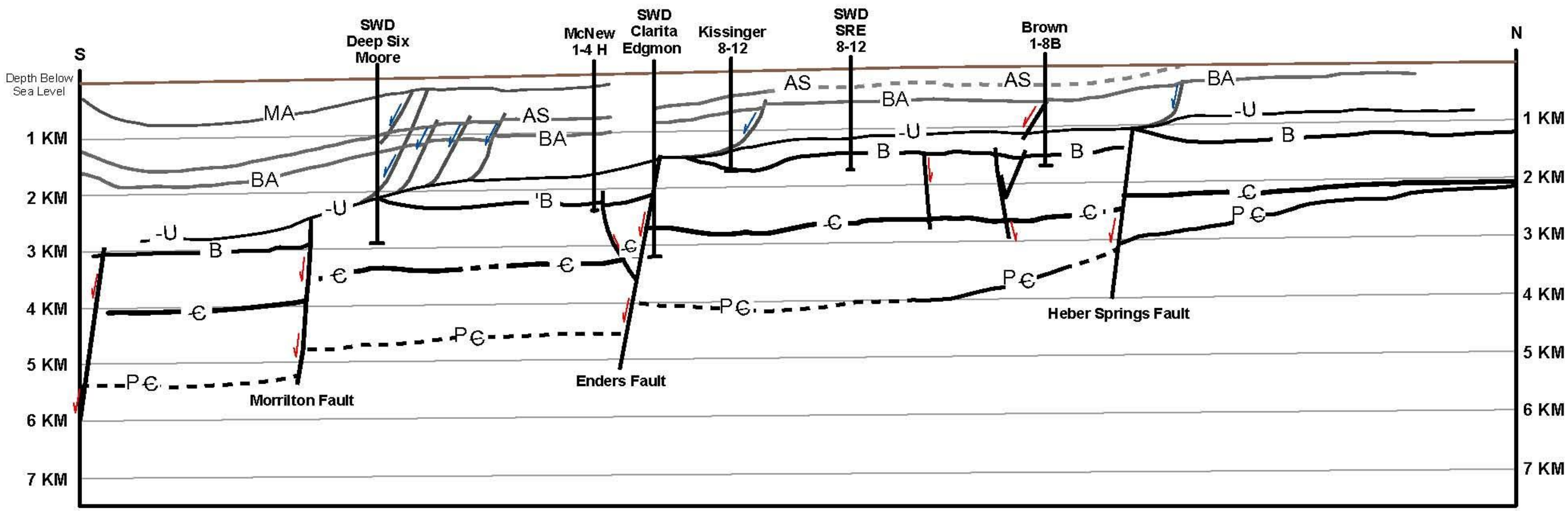
Located in the easternmost Arkoma basin of Arkansas, just north of the frontal thrust faults of the Ouachita transition zone. (Schweig, 1989)

Enola and Guy-Greenbrier Earthquake Swarm Areas

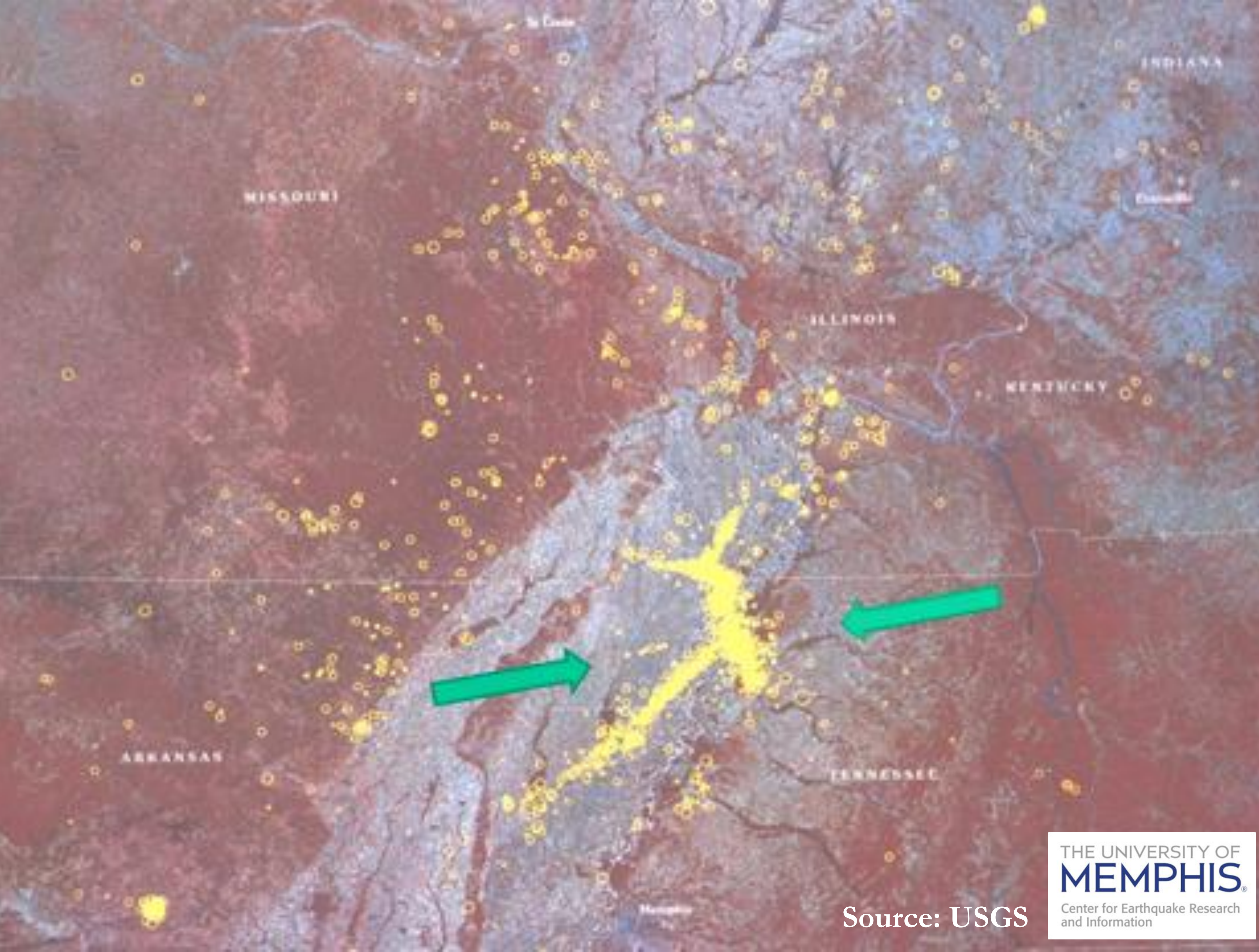



Van Buren
Shirley Fault
Shirley
Fairfield Bay
Clinton
Cleburne
Higden
Greers Ferry
Clinton Fault
Heber
Center Ridge Fault
Heber Springs Fault
Quitman
Damascus
Guy-Greenbrier Fault
Guy
Rose Bud
Twin Groves
Conway
Enders Fault
Faulkner
Greenbrier
Mount Vernon
Wooster
Enola
Morrilton Fault
Holland
Plumerville
Menifee
ARKANSAS GEOLOGICAL SURVEY

Structural Cross-Section



SOURCE: AAPG Bulletin V. 74 (July, 1990), P. 1030-1037, 4 Figs., 1 Table



Source: USGS

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Center for Earthquake Research and Information

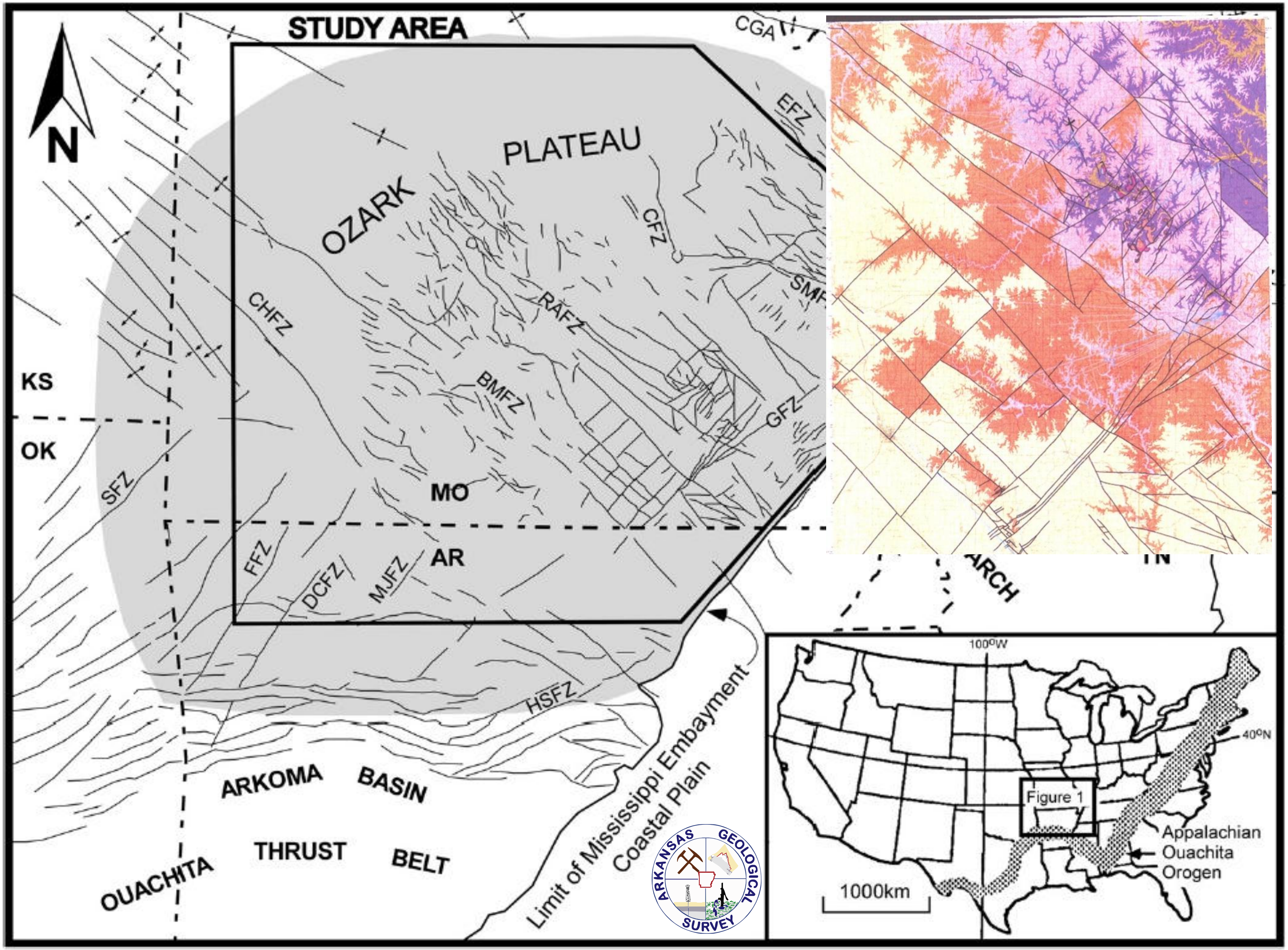
Orthogonal Fracturing in the Earth's Continental Crust

S. Parker Gay, Jr., 1973: summarized some 30 different studies in the literature pertinent to crustal fracturing:

- The earth's crust is cut by a number of set of parallel to sub-parallel "deep" fractures that occur pervasively throughout the globe – most if not all occurred in Precambrian time – these are typically paired with another set "orthogonal" to each other – "pairset" – and may have been reactivated numerous times (both in the Precambrian and in the Phanerozoic time

- Sedimentary rocks become jointed early in their history as a result of minor vertical movement along the basement pairsets by a "bridging mechanism" - this mechanism results in forming orthogonal tension joints in the overlying sedimentary rock – "mirroring" the causative basement fractures below

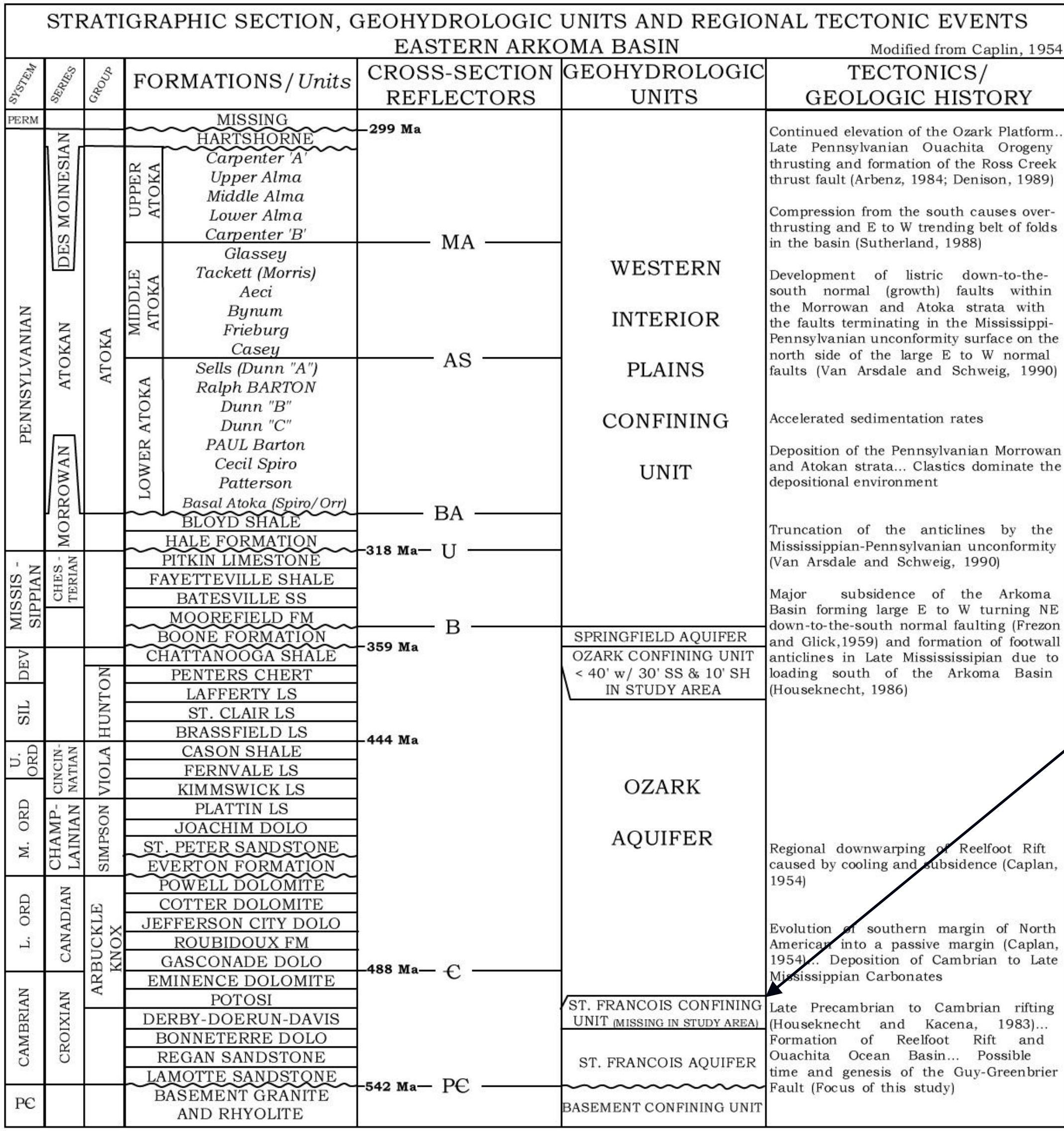
ARKANSAS GEOLOGICAL SURVEY


STUDY AREA
N
OZARK
PLATEAU
CGA
EFZ
CFZ
SMF
CHFZ
RAFZ
BMFZ
GFZ
KS
OK
SFZ
MO
AR
FFZ
DCFZ
MJFZ
ARCH
TN
HSFZ
ARKOMA
BASIN
THRUST
BELT
OUACHITA
Limit of Mississippi Embayment
Coastal Plain
100°W
40°N
Figure 1
Appalachian
Ouachita
Orogen
1000km
ARKANSAS GEOLOGICAL SURVEY

Plausible Hydraulic Connectivity

Source: Imes, J. L. and Emmett, L.F., USGS, 1994

- Tectonic activity and erosion results in uplift of the Ozark Plateau above sea level creating faults and fractures
- Major rift (New Madrid) forms on the southeast flank also contributes to regional faulting and fracturing
- Numerous faults and fractures exhibit preferential orientation to the northeast-southwest and northwest-southeast
- These faults and fractures provide avenues for ground water movement through virtually impermeable rock
- Many of the faults and fractures in the younger overlying Paleozoic rocks in the eastern portion of the Ozarks are the result of repeated differential movement across weak zones associated with the faults in the underlying basement faults



STRATIGRAPHIC SECTION GEOHYDROLOGIC UNITS

- **St. Francois Confining Unit is missing in the Study Area (Caplin, 1960)**

Were the Guy-greenbrier Earthquakes Triggered by fluid injection?

- The Guy-Greenbrier fault was critically stressed prior to the start of injection.

- Therefore, the Mohr-Coulomb criterion must have been changed incrementally (naturally or by human activity) shortly before or coincident with the earthquakes.

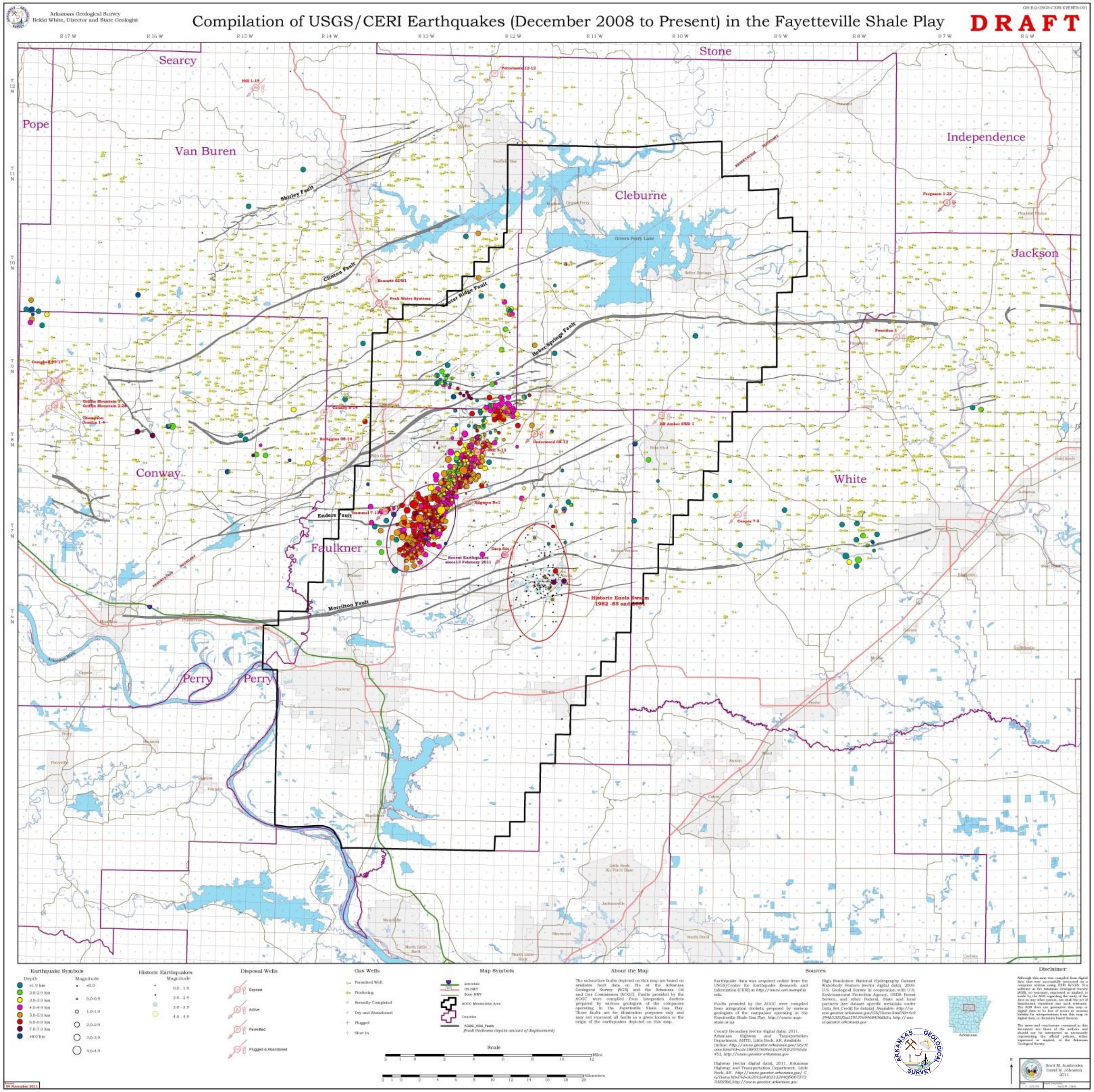
- The earthquakes along the Guy-Greenbrier fault began after the start of injection at well #1 with intense seismic activity following the start of injection at well #5.

Were the Guy-greenbrier Earthquakes Triggered by fluid injection? Continued…

- Earthquake frequency in the study area shows a strong correlation with the volume of injection at well#1 and well#5.

- The injection of fluids increased pore pressure in the Ozark aquifer, and because of the hydraulic connection between the Ozark aquifer and the Guy-Greenbrier fault, pore pressure could also have increased in the fault zone.

- Given the spatial and temporal correlation between the UIC wells and activity on the fault, it would be an extraordinary coincidence if the earthquakes were not triggered by fluid injection.



Compilation of USGS/CERI Earthquakes (December 2008 to Present) in the Fayetteville Shale Play
DRAFT
Arkansas Geological Survey
Bekki White, Director and State Geologist
Searcy
Stone
Pope
Van Buren
Cleburne
Independence
Jackson
Conway
White
Faulkner
Perry
Shirley Fault
Clinton Fault
Heber Springs Fault
Enders Fault
Morrilton Fault
Greers Ferry Lake
Recent Earthquakes since 13 February 2011
Historic Enola Swarm 1982 -85 and 2001
Earthquake Symbols
Historic Earthquakes
Disposal Wells
Gas Wells
Map Symbols
About the Map
Sources
Disclaimer
Scale

References and Sources:

Arkansas Geological Survey

Arkansas Oil and Gas Commission

Burroughs, R., K., 1988, Structural Geology of the Enola Arkansas Earthquake Swarm: Master Thesis, University of Arkansas.

Cox, R.T., 2009, Tectonophysics, 474, p 674-683.

Gay, Jr., Parker, S., 1973, Pervasive Orthogonal Fracturing in the Earth's Continental Crust.

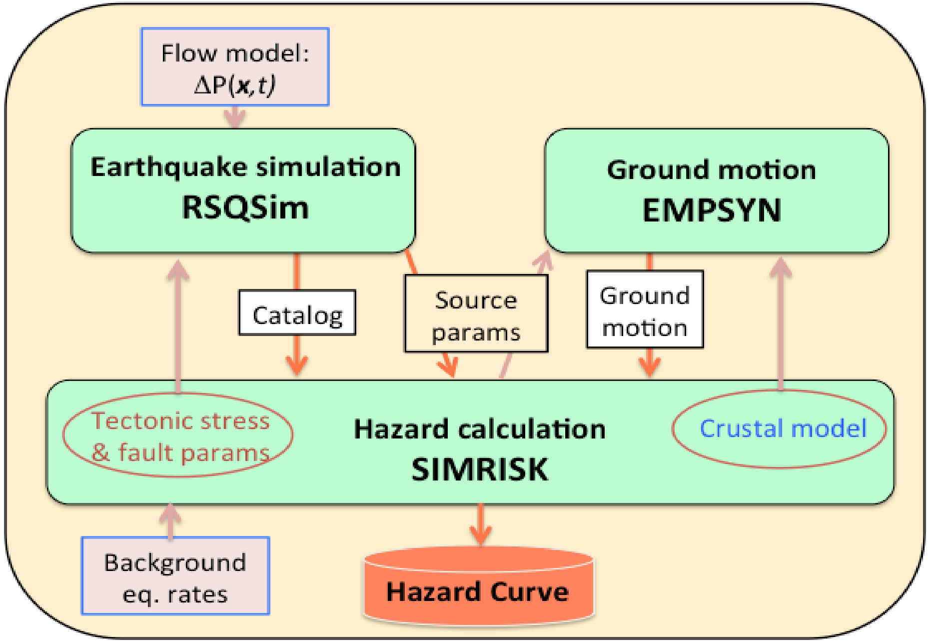
Harrison, R., 2009, USGS PowerPoint: History and Fabric of the Region Surrounding the Northern Mississippi Embayment and the New Madrid Seismic Zone: Midcontinent U.S.

Imes, J. L. and Emmett, L.F., 1994, Major geohydrologic units in and adjacent to the Ozarks Plateaus Province, Missouri, Arkansas, Kansas, and Oklahoma, U. S. Geological Survey Hydrologic Investigations Atlas, HA 711-A

VanArsdale, R.B. and Schweig, E.S., III, 1990. Subsurface structure of the Eastern Arkoma Basin, The American Association of Petroleum Geologists Bulletin, V. 74, No. 7 (July 1990), P. 1030-1037, 4 Figs., 1 Table.

Thank You for your Attention

Any Questions ???



Research in Induced Seismicity

Grant Bromhal, NETL

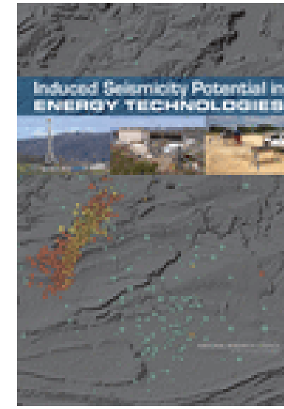
GWPC Annual UIC Meeting

January 22-24. 2013

U.S. DEPARTMENT OF ENERGY

NETL

NAS Study on Induced Seismicity



- **Three major findings emerged from the study:**
  - hydraulic fracturing does not pose a high risk
  - waste water disposal does pose some risk, but frequency of known events is low
  - CCS may have potential for inducing seismic events, but much is unknown.
- **"Methodologies can be developed for quantitative, probabilistic hazard assessments of induced seismicity risk."**
- **Need for federal agencies to coordinate on induced seismicity response.**

Outline

- Intro to NRAP and quantitative methods for predicting induced seismicity risks
- Induced Seismicity and Fault Leakage
- Federal Agency Cooperation

Outline

- **Intro to NRAP and quantitative methods for predicting induced seismicity risks**
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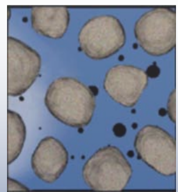
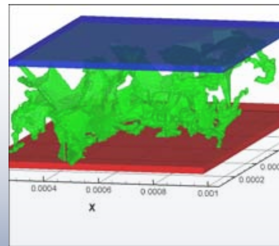
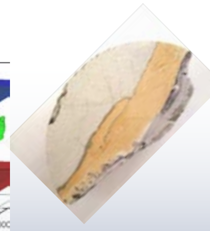
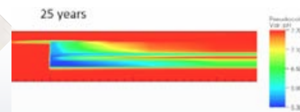
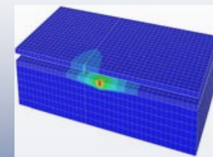
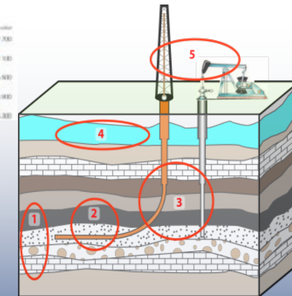


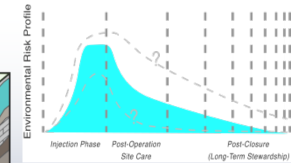












National Risk Assessment Partnership

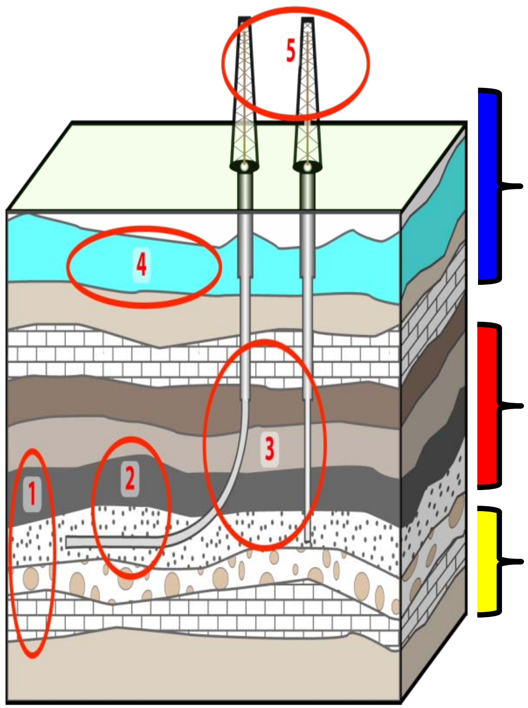
Wade, LLC

Technical Team

Stakeholder Group

Approach to quantifying system performance is to use integrated assessment models (IAMs) to couple behavior of each component.

A. Divide system into discrete components



Potential Leakage Impacts
(Atmosphere; Groundwater)

⇧ **fluid propagation**

Release/Transport of Fluids

⇧ **fluid propagation**

Reservoir
(plume/pressure evolution)

Potential Ground-Motion Impacts
(Ground Acceleration)

⇧ **seismic-wave propagation**

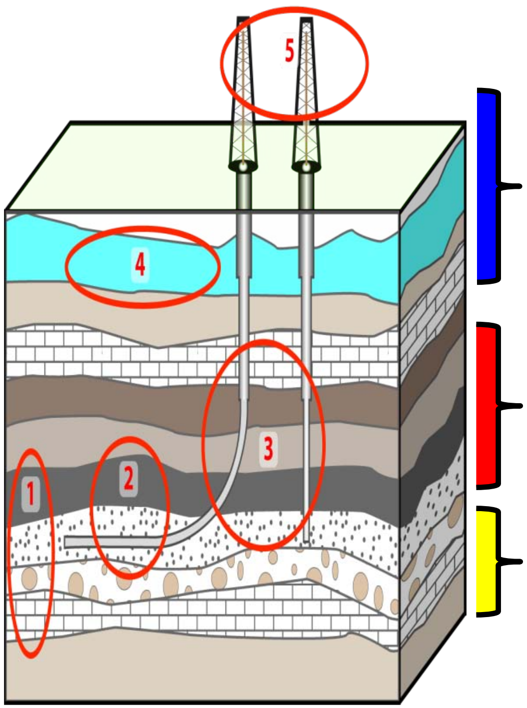
Slip along a Fault Plane

⇧ **stress/pressure propagation**

Reservoir
(plume/pressure evolution)

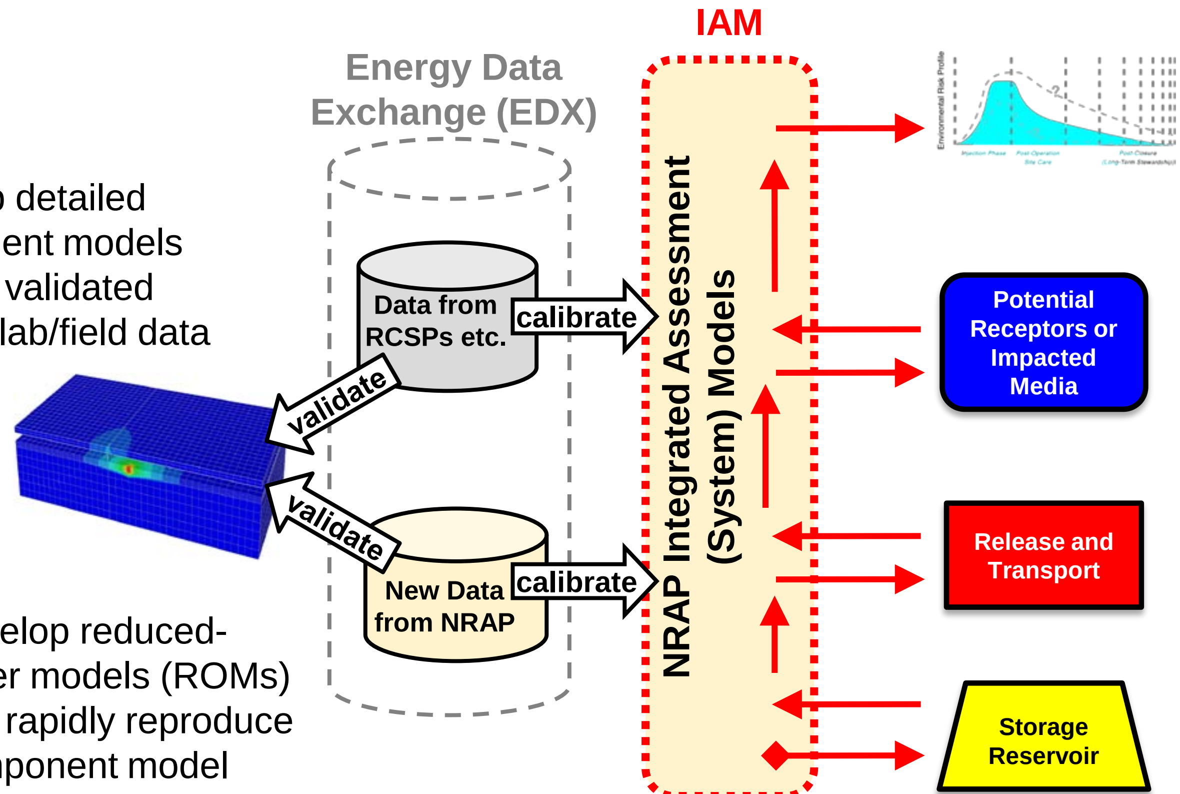
NRAP Approach to Quantifying System Performance

A. Divide system into discrete components



B. Develop detailed component models that are validated against lab/field data

C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions



D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

E. Develop strategic monitoring protocols that allow verification of predicted system performance

Elements of Traditional Probabilistic Seismic Hazards Assessment

- Identify potential earthquake sources (faults).
- Characterize the rates at which earthquakes of various magnitudes are expected to occur
- Characterize the distribution of source-to-site distances for potential earthquakes.
- Predict the distribution of ground motion intensity as a function of earthquake magnitude, distance, etc.
- Combine uncertainties in earthquake size, location and ground motion intensity, using ‘the total probability theorem’.

From J.W. Baker (2008)

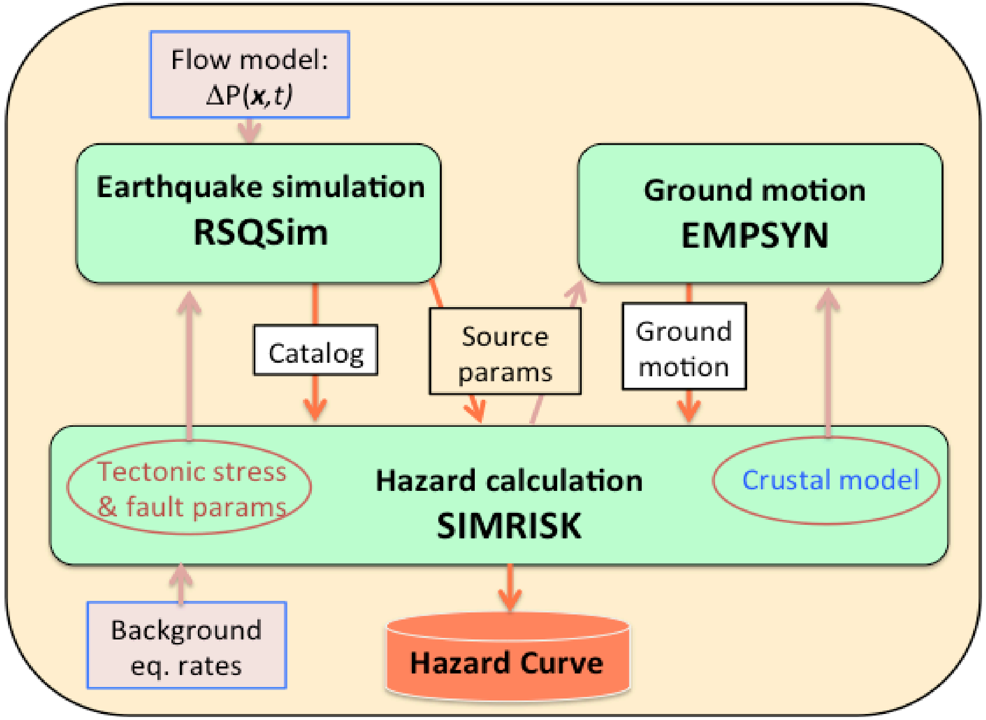
Adapting PSHA for induced seismicity

	Tectonic	Induced
Frequency-magnitude distribution	historical eq. catalog	**no catalog prior to injection**
	assumed Poissonian	**non-uniform in time and space**
M_{min}	4-4.5	1-2.5
Depth	deep (>5 km)	shallow (~1-5 km)
Distance	>5 km	~1 km
GM frequency	0.1-20 Hz	1-100 Hz
GM estimation	empirical*	**local, site-specific**

Global ground motion prediction relations are very poorly constrained at short distances and small magnitudes

Foxall et al (2012), Annual CCUS

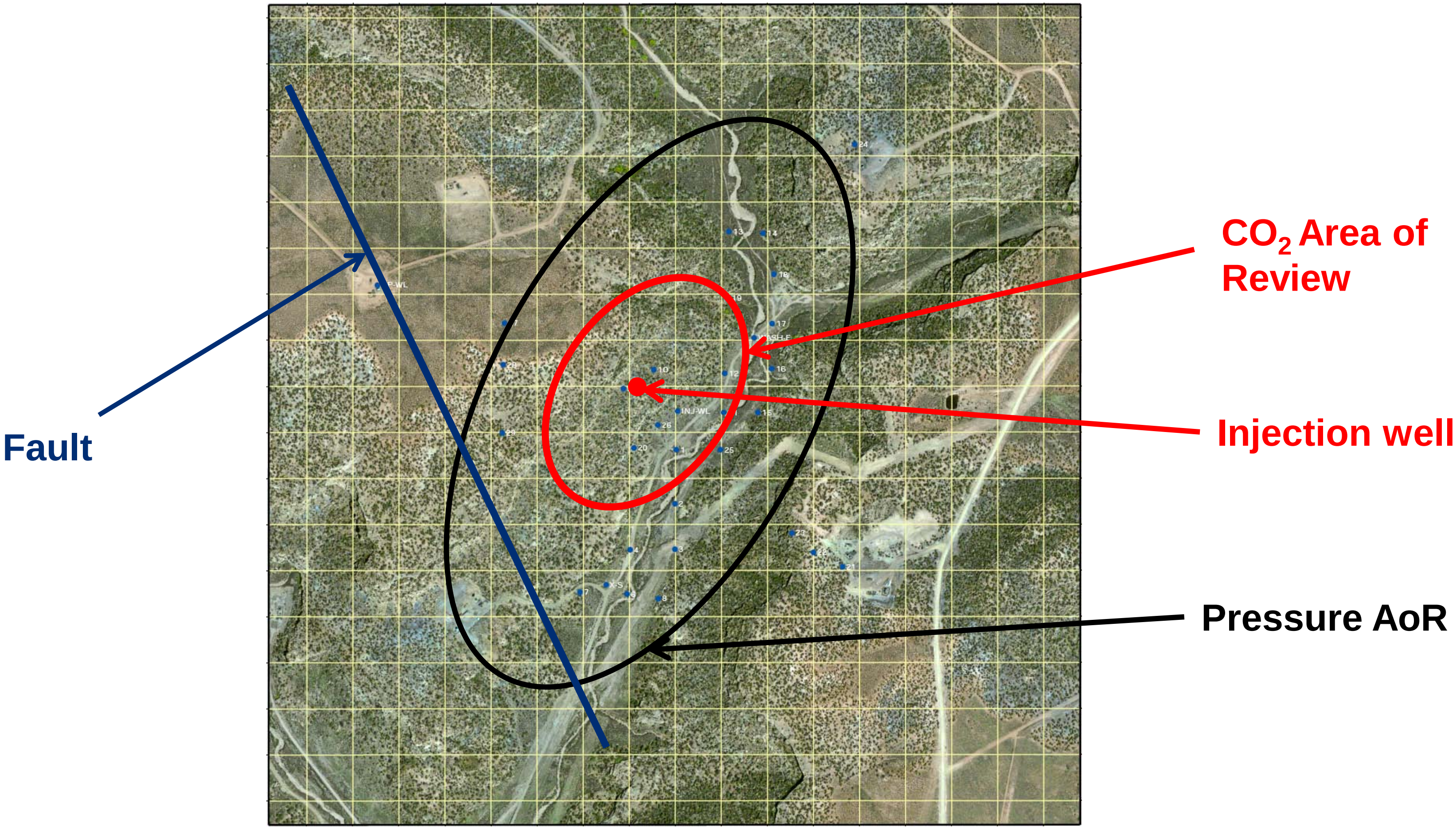
Integrated Assessment Model for PSHA



- **RSQSim**[1]—simulates tectonic earthquakes and slow slip events on faults, adapted to use time-dependent pore pressure changes
- **EMPSYN**—calculates ground accelerations and velocities
- **SIMRISK**—calculates a frequency-magnitude distribution

[1]Dieterich and Richards-Dinger, 2010

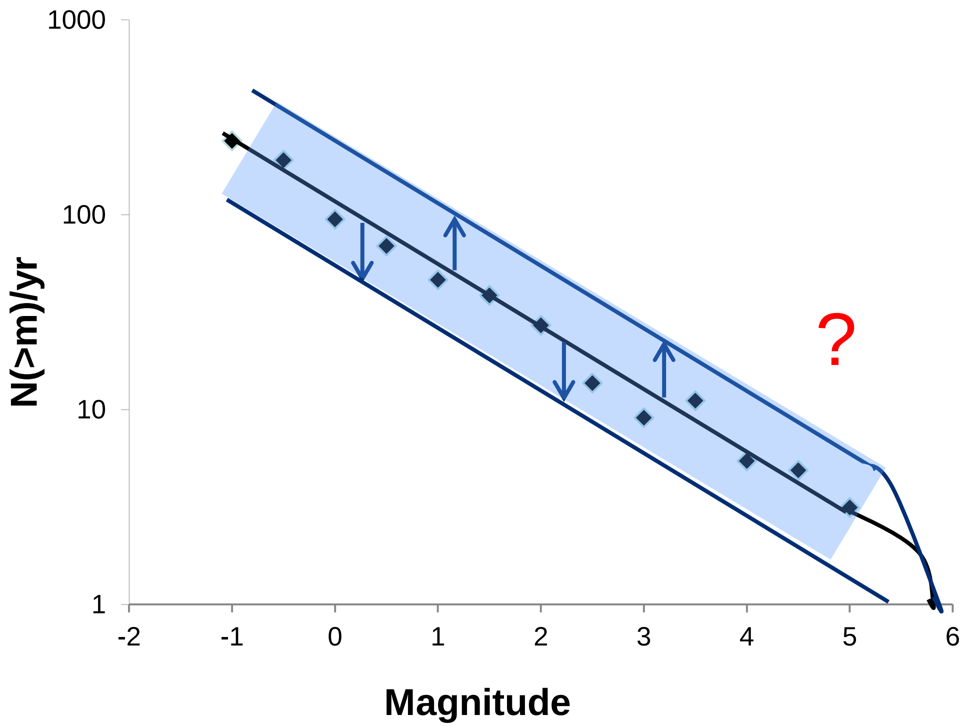
Will the pressure front influence existing faults?



Region of interest for IS will depend on pore pressure changes and *in situ* stresses

- EPA Proposed Rule, 2008

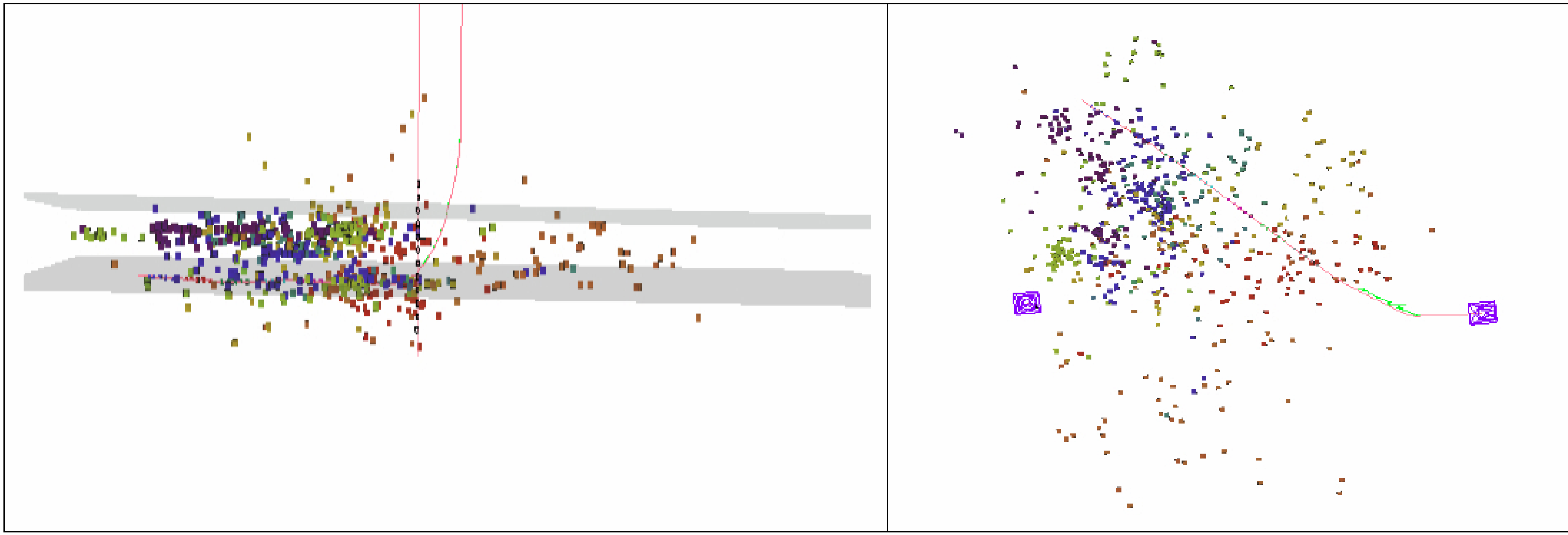
Will injection/production affect the frequency-magnitude relationship?



Gutenberg-Richter relationship: $\log N(>m) = a - bm$

Simplified model relationship

Microseismic monitoring may help understand frequency-magnitude relationships.

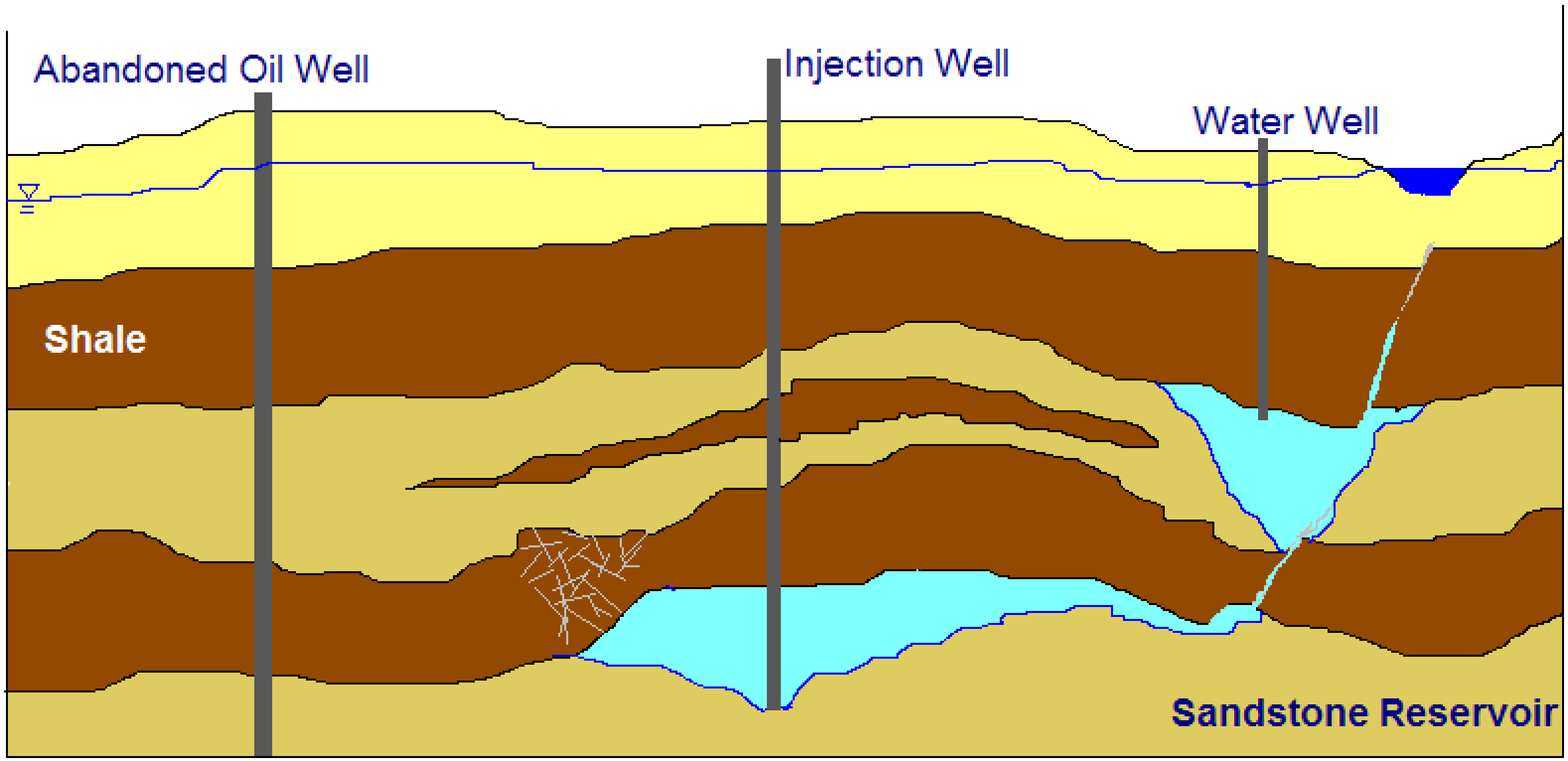


Side View

Top View

SPE 135262

Will fault permeability be affected?



- Experimental work aimed at assessing changes to fault permeability
- Simulation work aimed at predicting rate (if any) of CO_2 to reach USDW

NRAP Induced Seismicity Capabilities Development Plan

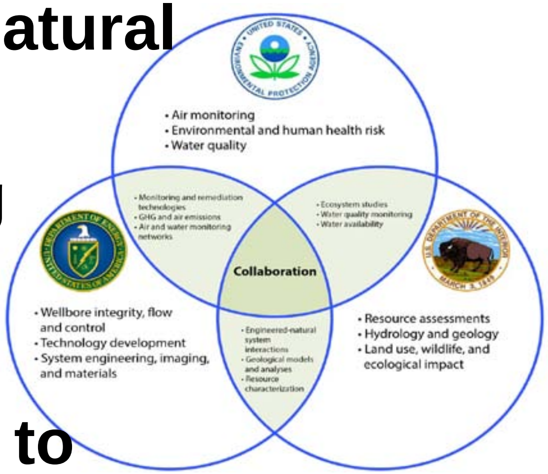
- **Generation 1 (July 2012)—IAM for Probabilistic Seismic Hazards Assessment for single fault**
- **Generation 2—IAM for PSHA (Spring 2013)**
  - Multiple faults
  - Multiple time periods
  - Calculation of nuisance risk
  - Parameter sensitivity calculations
- **Generation 3—IAM for PHSA and risk**
  - Higher frequencies in ground motion
  - Full risk
  - Ties to fault leakage risk

Outline

- Intro to NRAP and quantitative methods for predicting induced seismicity risks
- Induced Seismicity and Fault Leakage
- Lessons from CCS Best Practice Manuals
- **Federal Agency Cooperation**

Interagency Collaboration

- **DOE, USGS, EPA have had a recent discussion on unconventional resource R&D**
- **Induced seismicity was identified as an area for collaboration**
- **DOE and USGS have ongoing efforts in natural and induced seismic hazards analysis**
- **Main EPA interest is in regulation; strong interest in applying research results**
- **Proposed annual collaborative meetings between agencies and with other players to assess gaps/needs**



Thank You!

- Questions?

- bromhal@netl.doe.gov

INDUCED SEISMICITY AND THE O&G INDUSTRY

This presentation represents the collective thoughts of subject matter experts drawn from AXPC member companies and other Oil and Gas Industry companies. The subject matter experts include geologists, geophysicists, hydrologists, and regulatory specialists. This presentation does not represent the views of any specific trade association or company.

GWPC
January 23, 2013

Purpose

- Provide a primer on natural and potentially induced seismicity
- Provide a general discussion on the potential of O&G induced seismicity from hydraulic fracturing and the disposal of fluids by underground injection
- Describe a framework to consider in screening, assessing, monitoring, and mitigating seismicity from fluid injection for disposal, where induced seismicity is suspected and/or there are heightened concerns due to local conditions

Seismicity 101

- Seismicity (natural or induced) is the shaking of the earth due to a slip on a fault caused by the release of stored elastic stress
- Seismicity can be induced or triggered when changes in stress or pore pressure promote a slip
- Most all seismicity is too small to be measured or felt by humans and does not cause damage to man-made structures
- The term induced seismicity is used when referring to seismicity linked to human activities

Natural Seismicity

- Seismic events occur with varying degrees of intensity…many more smaller than larger
- The energy released may reach the earth surface and cause noticeable shaking
- Damage to structures, if any, depends on the amount of energy reaching the surface, geomechanical characteristics of the soil and the condition of the structures
- The *epicenter* is the location at the surface above the slip event
- The *hypocenter* is the event's actual location in the subsurface

Measuring Seismicity

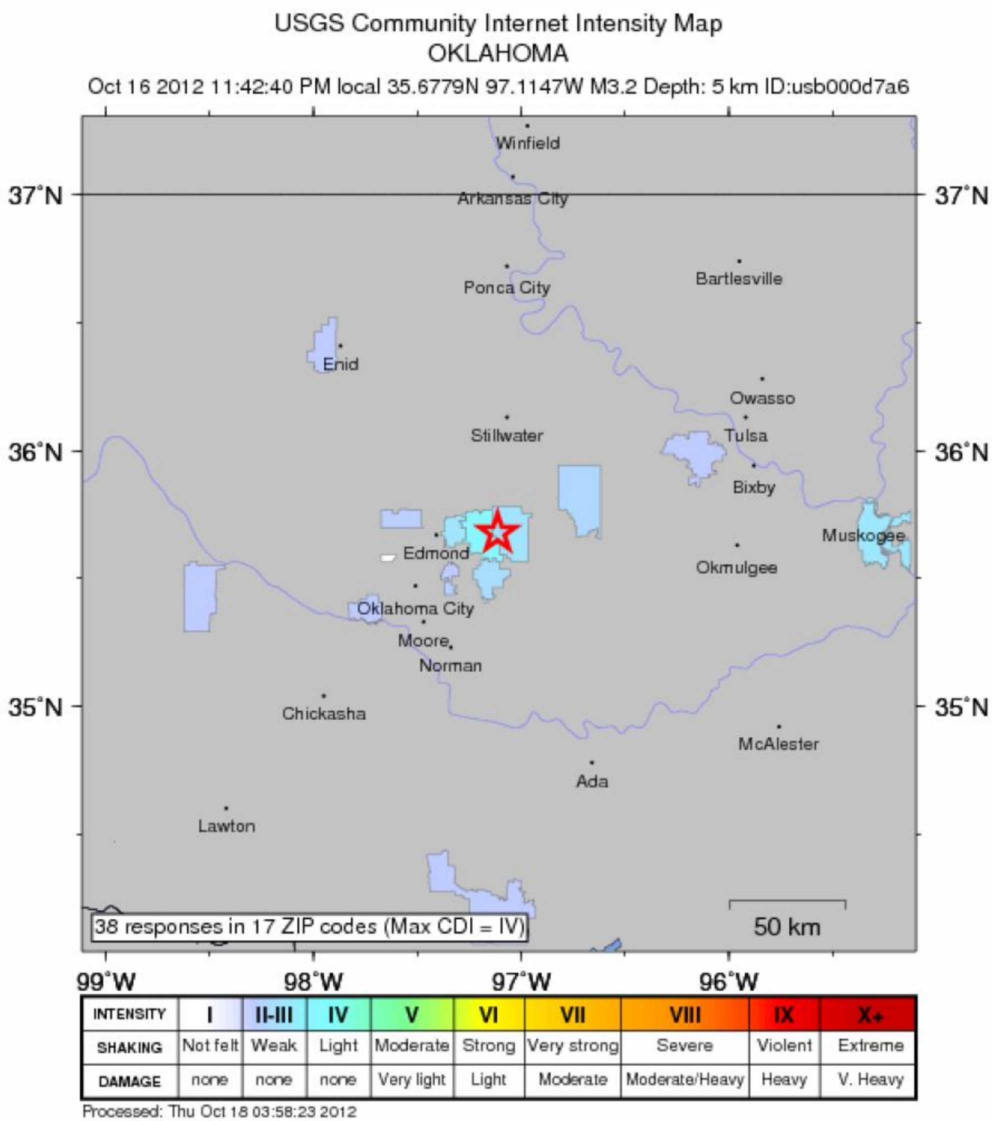
- The Richter Scale*
  - This scale is logarithmic: each increase of one unit represents a 10-fold increase in the amplitude of seismic waves measured by a seismograph (and approximately 30 times the energy released)
  - This scale has no theoretical limits: magnitude of recorded natural events typically ranges from -3 (the lower limit of micro-seismic sensor sensitivity) to 9 + (the most severe earthquake ever recorded)

** And its modern equivalents e.g. local magnitude, moment magnitude*

Measuring Seismicity

- The Modified Mercalli Index (MMI)
  - Uses the perceived effects of a seismic event on the people and structures in a given area to determine its intensity
  - Defines 12 levels of seismic event severity, ranging from imperceptible to devastating
  - MMI level is **not** synonymous with the Richter Scale magnitude, but is more useful in describing actual local effects
  - Depends upon many factors including: depth of the seismic event, distance from the seismic event epicenter, geomechanical characteristics, terrain, population density

Measuring Seismicity – Local Effects



- USGS ShakeMap
- Magnitude 3.1
- Max MMI intensity IV
- 38 Responses - 17 Zip codes

Comparison of Seismic Scales

Richter Magnitude	Description	MMI	Earthquake effect observations	World-wide occurrence
< 2.0	Micro		Micro earthquakes not felt by people and detected by sensitive instruments only.	Continual >8,000 per day
2.0 – 2.9	Minor	1	Imperceptible: Not felt except by a very few people under exceptionally favorable circumstances.	1,300,000 per year (est.)
3.0 – 3.9		2	Scarcely felt: Felt by only a few people at rest in houses or on upper floors buildings.	130,000 per year (est.)
		3	Weak: Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognized as an earthquake.	
4.0 – 4.9	Light	4	Largely observed: Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic. Walls may creak; doors, windows, glassware and crockery rattle.	13,000 per year (est.)
		5	Strong: Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.	
5.0 – 5.9	Moderate	6	Slightly damaging: Felt by all. People and animals alarmed. Many run outside. Walking steadily is difficult. Objects fall from shelves. Pictures fall from walls. Furniture may move on smooth floors. Glassware and crockery break. Slight non-structural damage to buildings may occur.	1,319 per year
		7	Damaging: General alarm. Difficulty experienced in standing. Furniture and appliances shift. Substantial damage to fragile or unsecured objects. A few weak buildings damaged.	
6.0 – 6.9	Strong	8	Heavily damaging: Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.	134 per year
7.0 – 7.9	Major	9	Destructive: Some buildings are damages and many weak buildings are destroyed.	15 per year
8.0 – 8.9	Great	10	Very destructive: Many buildings are damaged and most weak buildings are destroyed.	1 per year
		11	Devastating: Most buildings are damaged and many buildings are destroyed.	
9.0 – 9.9		12	Completely devastating: All buildings are damaged and most buildings are destroyed.	1 per 10 years (est.)
10.0+	Massive	>12	Never recorded, widespread devastation across very large areas.	Unknown

Created from USGS information by Wikipedia

Induced Seismicity

- Induced seismicity is seismicity due to human activity
- An increase in local seismicity that has spatial and temporal correlation with human activities raises the possibility of it being induced
- To assess whether or not the seismic activity is induced, it is necessary to evaluate the seismic data, the geophysical and geomechanical mechanisms surrounding the seismic events, as well as operational evidence
- In order for induced seismicity to take place there needs to be a critically stressed fault near the human activity

Induced Seismicity

- A small number of induced seismicity cases have been attributed to the following human activities:
  - Enhanced geothermal systems
  - Construction
  - Mining
  - Dams and reservoirs
  - Hazardous waste injection for disposal
  - Oil and Gas activities

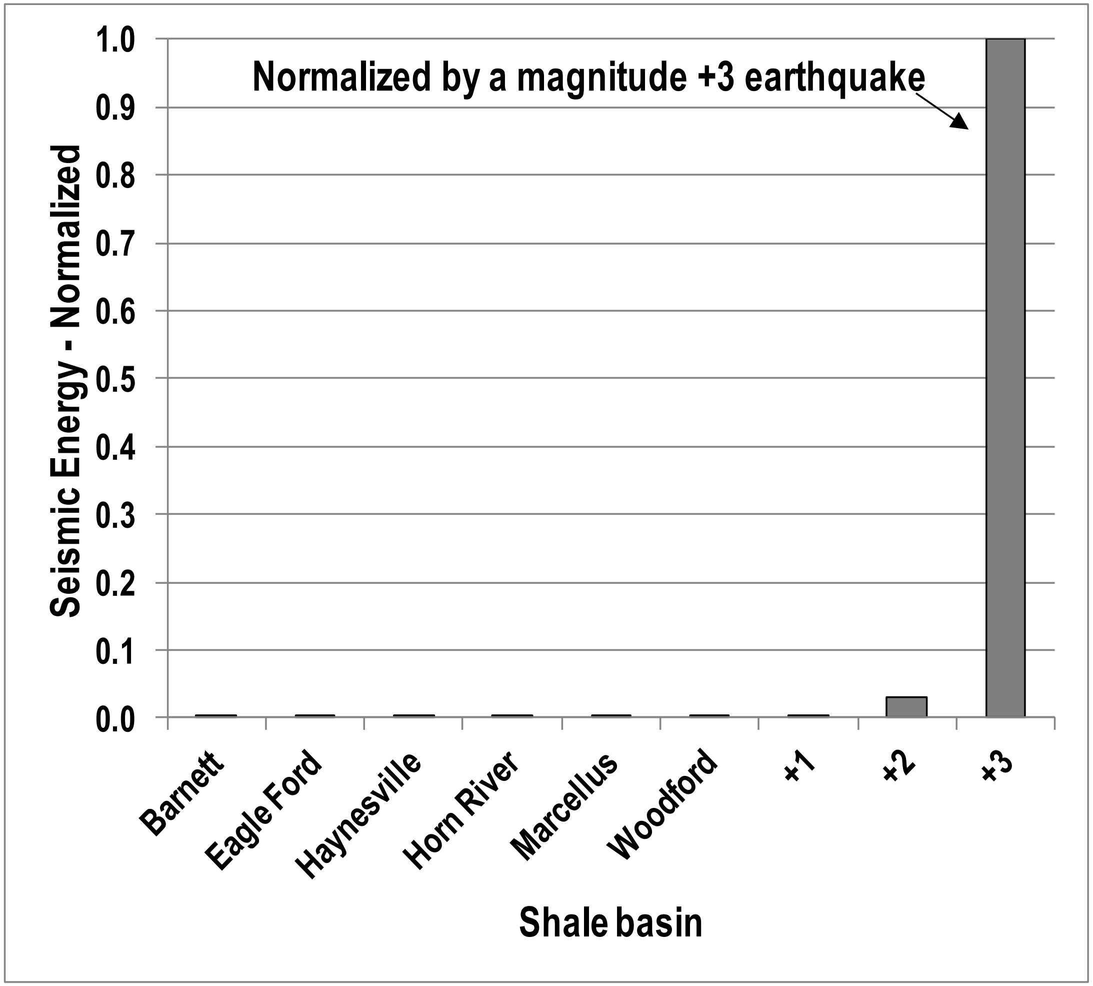
Induced Seismicity – Oil and Gas

- Production and enhanced oil recovery
  - Rare cases – water floods and production associated subsidence
  - Injection raises in-situ stress – withdrawal reduces in-situ stress
  - Has been managed by controlling injection pressures and rates
- Hydraulic fracturing
  - Short term/low volumes – process lasts 1-5 days per well
  - Process produces microseismic events, but very rarely felt at surface
    - 3 events recognized out of over 1 million fracturing operations
    - Associated with hydraulic fracturing near basement structure and/or near a critically stressed fault

"The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events" –

National Academy of Sciences - 2012

Induced Seismicity – Hydraulic Fracturing



Warpinski et al. 2012
SPE 151597

Normalized maximum microseismicity energy induced by hydraulic fracturing compared to a magnitude +3 earthquake, which is similar to the passing of a nearby truck

AXPC / Industry induced seismicity SME presentation

Induced Seismicity

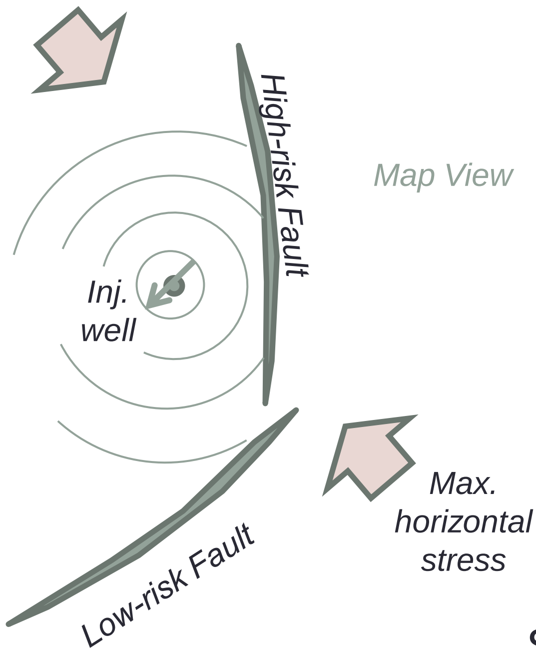
Fluid Disposal using Underground Injection (UIC Class II)

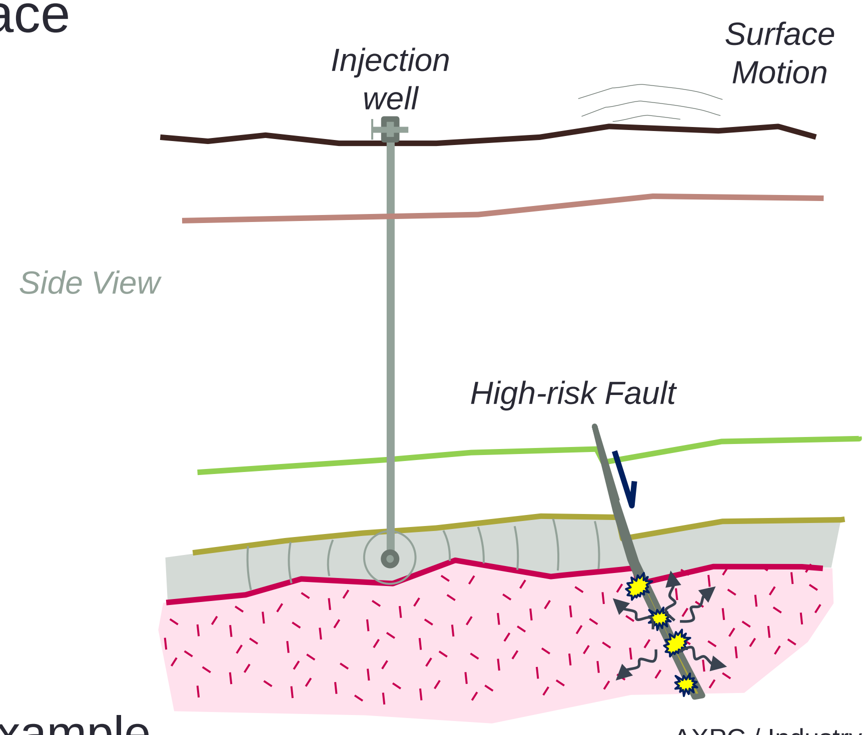
- UIC Class II wells are regulated by Federal/State Underground Injection Control Program
- There are over 30,000 UIC Class II disposal wells operating in the US……few proven cases of induced seismicity
  - Felt events are associated with injection near basement* structure and/or a critically stressed fault
  - Induced seismicity can be managed with operations monitoring and modulation of injection pressures and rates

* The term "basement" is used to define any rock below sedimentary rocks or sedimentary basins that are metamorphic or igneous in origin.

Induced Seismicity – Fluid Injection

- Fluid injection: raises pore pressure in subsurface
- Increased pressure reaches a nearby critically stressed fault with a high-risk orientation
- Fault reacts: brittle deformation, especially in basement rock, radiates seismic waves
- Ground motion may result at surface





Schematic example

AXPC / Industry induced seismicity SME presentation

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation

- Risk management process for fluid disposal wells (UIC Class II)
  - Where significant induced seismicity is suspected and/or concerns due to local conditions – MOST ALL DISPOSAL WELLS HAVE NO SEISMICITY

- Highlights:
  - Proactive approach addressing public and regulatory concerns
  - Screening for siting new disposal wells
  - Not intended for legacy wells not suspected of induced seismicity
  - Scalable process for varying local conditions including: geology, operations, demographics
  - Dynamic – evolves as conditions change
  - Plan for mitigation, if and when, potentially induced seismicity occurs

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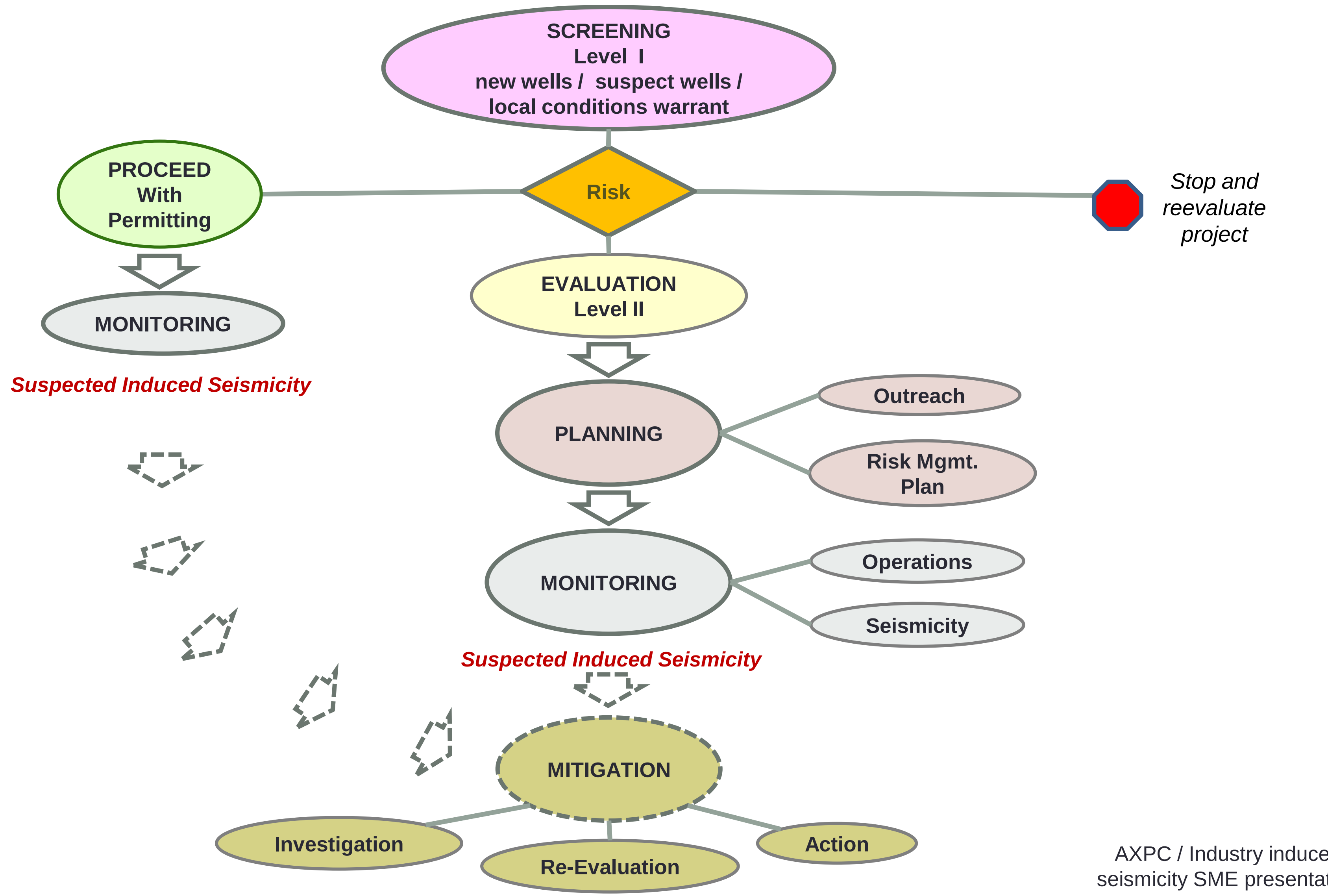
Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



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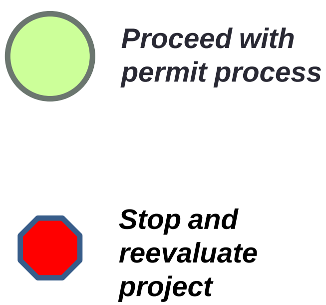
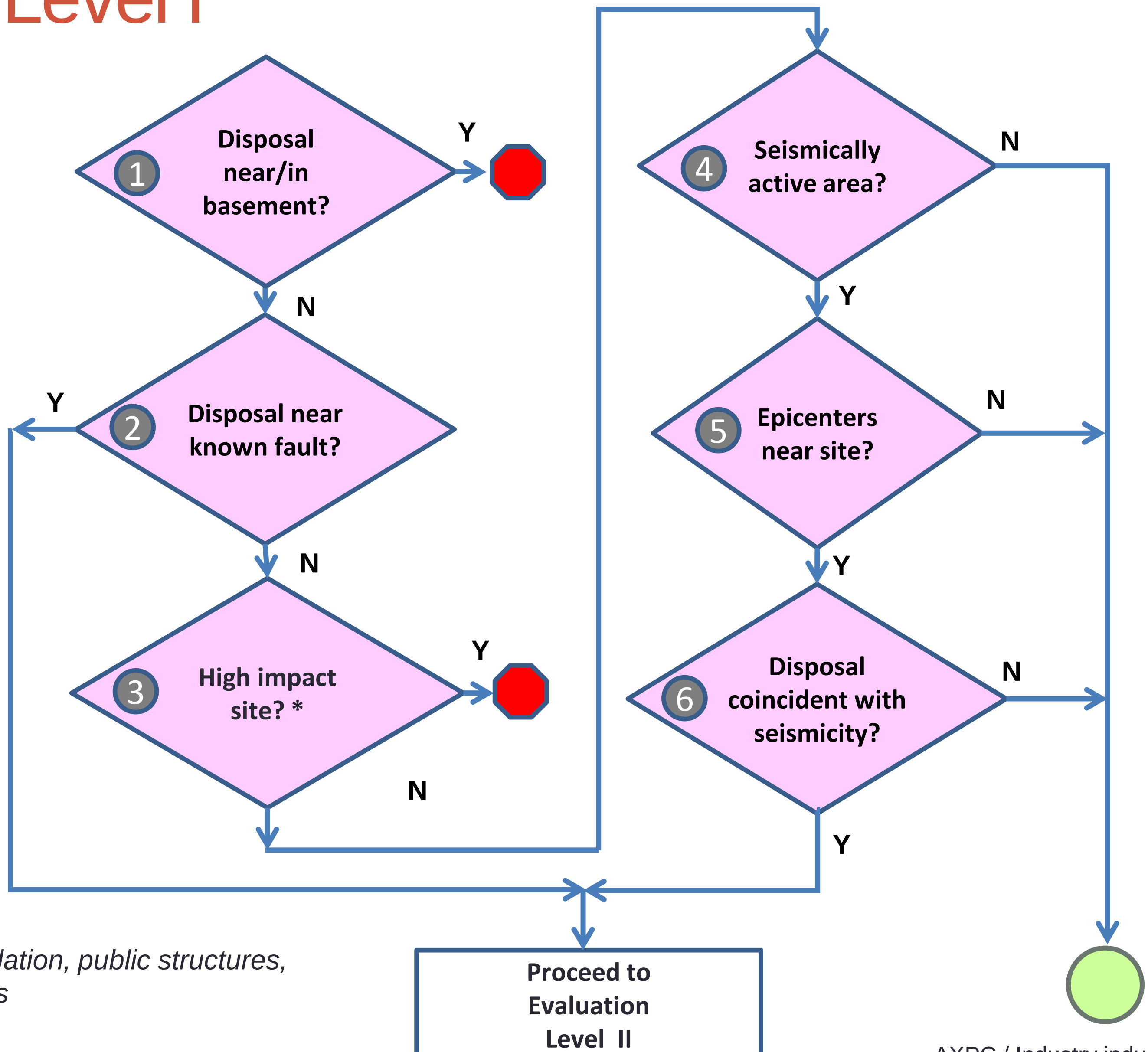
Screening – Level I

- New wells
- Wells suspect of induced seismicity
- Local conditions warrant



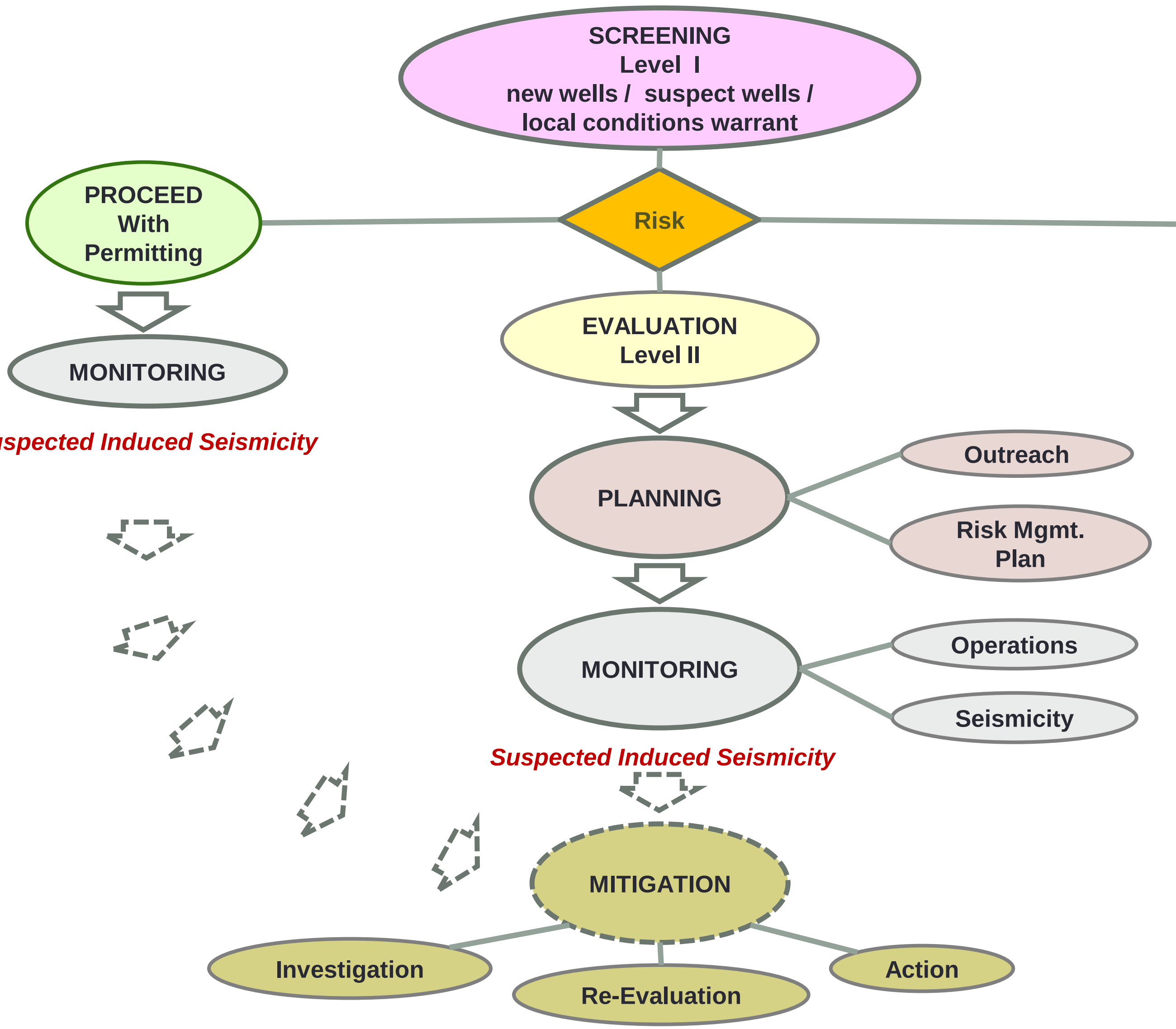


* e.g. Proximity to dense population, public structures, environmentally sensitive sites

Test criteria modified from Davis & Frohlich 1993

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



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Evaluation - Level II

- Hazard – The possibility of seismic events and ground motion occurring as a result of fluid disposal

- Impact – The effect on local population, property, or environment, including distress, damage, or loss

Evaluation Level II – technical considerations

Hazard

1. Local seismicity – location, depth
2. Local geologic stress and faults
3. Geomechanical modeling
4. Reservoir characteristics
5. Seals and boundaries, separation from basement
6. Pore pressure and fracture gradient
7. Ground conditions and expected seismic motion
8. Planned disposal volumes, rates, and pressures

Impact

1. Susceptibility of population, infrastructure, environment
2. Shake maps and damage models
3. Operator and stakeholder losses and liabilities
4. Probabilistic analyses of hazard and impact

Evaluation - Hazard Evaluation Toolbox *

Item	Data, Resources and Tools
Key geologic horizons and features	Data from existing wells, reflection/refraction seismic data, and gravity/magnetic data. Fault presence assessment from mapped horizons and coherency 'ant tracking'.
Regional stress assessment	World stress map, Stress literature, physical measurement, stress estimates from seismic and/or nearby well logs. Model effect on the reservoir and surrounding rocks from stress changes associated with fluid injection.
Surface features	USGS geological maps, published reports.
Ground conditions	Consolidation, saturation, composition, proximity to basement from State and USGS maps.
Ground response	Expected peak velocities, acceleration, and spectral frequency. Refer to local civil engineering codes. Models from USGS, state agencies and academia.
Local seismic events	Academic (e.g. IRIS), State, and industry surveys. If not available then regional or local dedicated network of seismometers and ground motion sensors. Establish magnitude, frequency of occurrence, and ground motion relationships.
Reservoir characterization	Rock type, facies, age, matrix composition, porosity types, depth, thickness, and petrophysical properties. Lateral extent and continuity, proximity to outcrop, proximity to basement, lateral barriers and conduits, compartments, bounding layers and intervening formations to basement, sealing rocks in system.
Reservoir properties	Permeability, porosity, natural fracture porosity, storativity. Mechanical properties: fracture gradient, closure pressure (ISIP), Young's Modulus, Poisson's Ratio, cohesion, coefficient of friction, pore pressure, lithostatic pressure, hydrostatic pressure, horizontal stress magnitudes and azimuth.
Disposal conditions	Initial saturation, salinity, pore pressure, static fluid level. Fluid injection rates, pressures, cumulative volumes

** Toolbox contains various scalable tools user can select to fit for purpose*

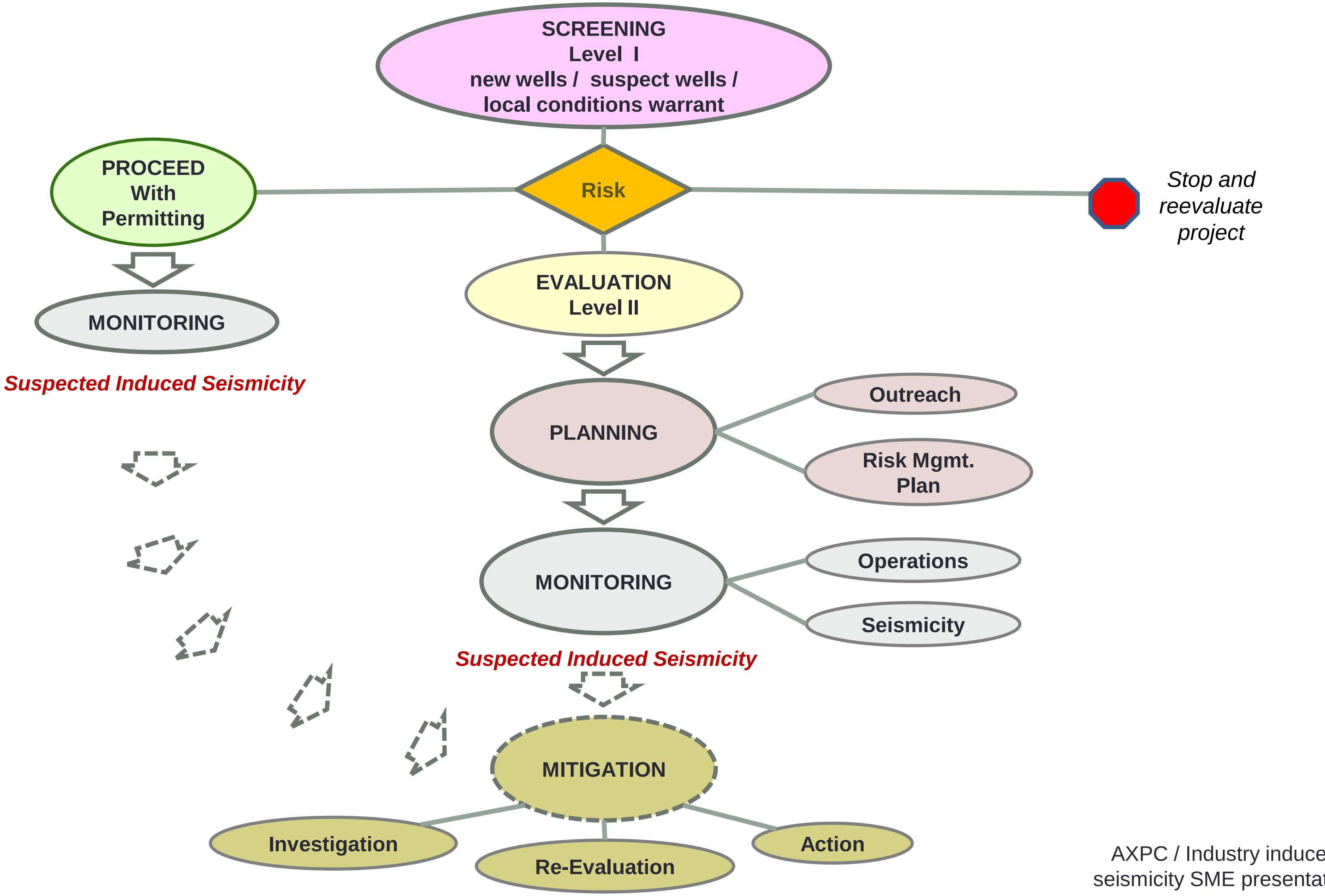
Evaluation – Impact Evaluation Toolbox *

Item	Data, Resources and Tools
Population	Survey 10 mile radius, nearby population centers. Assess the regional population density. Comfort or familiarity with seismic events – assess potential nuisance thresholds
Structures and Infrastructure	Summary of buildings, roads, pipelines, electric grid Critical infrastructure – e.g. Hospitals, schools, historical sites Construction practices, materials Local codes, seismic event ready?
Dams, Lakes, Reservoirs	Presence of dams, reservoirs. Ages, type of impoundment History of fill/drawdown Substrate – material and known faults
Environmental	General description of local ecology Special environmental hazards, protected species
Intangible	Goodwill, trust, reputation
Risk	Probabilistic models with both chance of occurrence and estimated ranges of potential outcomes for damage assessments, e.g. from HAZUS (USGS)

** Toolbox contains various scalable tools user can select to fit for purpose*

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



AXPC / Industry induced seismicity SME presentation

Planning

- Scalable and fit for purpose for the risk of induced seismicity
- Key elements in plan:

1. Conduct **Outreach** to partners and regulators
2. Establish motion thresholds for **Risk Management Plan** “Traffic Lights”

Planning - Outreach

- Communications plan – community and agencies

1. Identify local, State, and Federal agencies and expectations
2. Know regulatory requirements
3. Notification plan – whom, messages, response

Plan adaptable to local conditions and rules

Planning - Risk Management Plan: Traffic Lights

Green	Continue operations – no seismicity felt at surface (MMI I-II)*
Amber	Modify operations – seismicity felt at surface (MMI II-III+)*
Red	Suspend operations – seismicity felt at surface with distress and/or damage (MMI V+)*

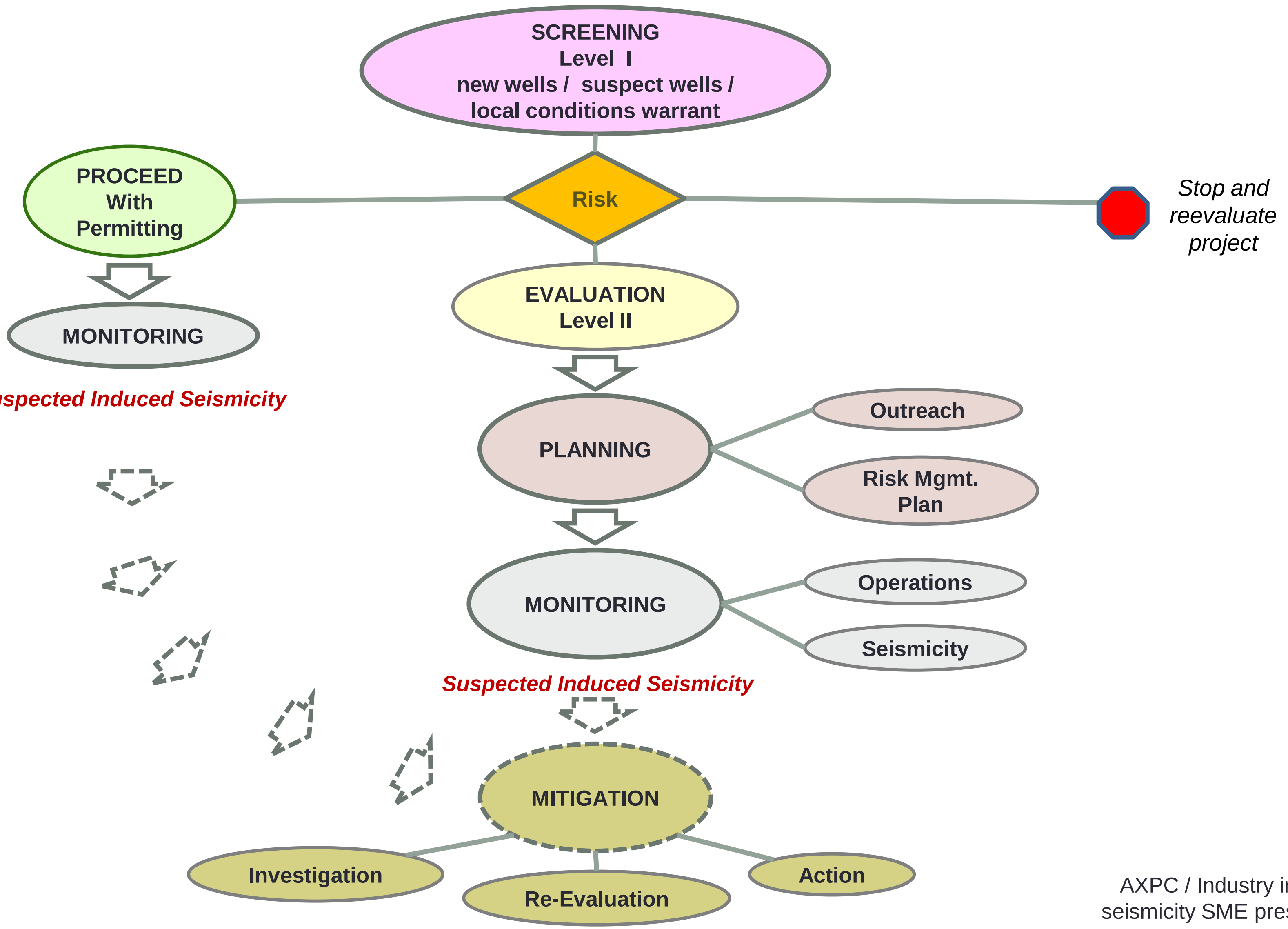
Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	none	none	none	Very Light	Light	Moderate	Moderate Heavy	Heavy	Very Heavy
Peak Acceleration (%g)	<0.17	0.17 to 1.4	1.4 to 3.9	3.9 to 9.2	9.2 to 18	18 to 34	34 to 65	65 to 124	>124
Peak Velocity (cm/s)	<0.1	0.1 to 1.1	1.1 to 3.4	3.4 to 8.1	8.1 to 16	13 to 31	31 to 60	60 to 116	>116
Magnitude	1 – 2.9	3 – 3.9	4 – 4.4	4.5 – 4.9	5 – 5.4	5.5 – 5.9	6 – 6.4	6.5 – 6.9	7.0+
Modified Mercalli	I	II to III	IV	V	VI	VII	VIII	IX	X+

Traffic Lights *

* *Established based upon local conditions, demographics and codes*

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



AXPC / Industry induced seismicity SME presentation

Monitoring

- Operations
  - Injection volume daily, cumulative
  - Injection pressure
  - Reservoir engineering evaluation
- Seismicity
  - Public monitoring
- Scalable and fit for purpose for the risk of induced seismicity
- Integrated with Risk Management Plan
  - Thresholds for ground motion
  - Seismic alerts (e.g. from USGS, local arrays)

Monitoring – Toolbox *

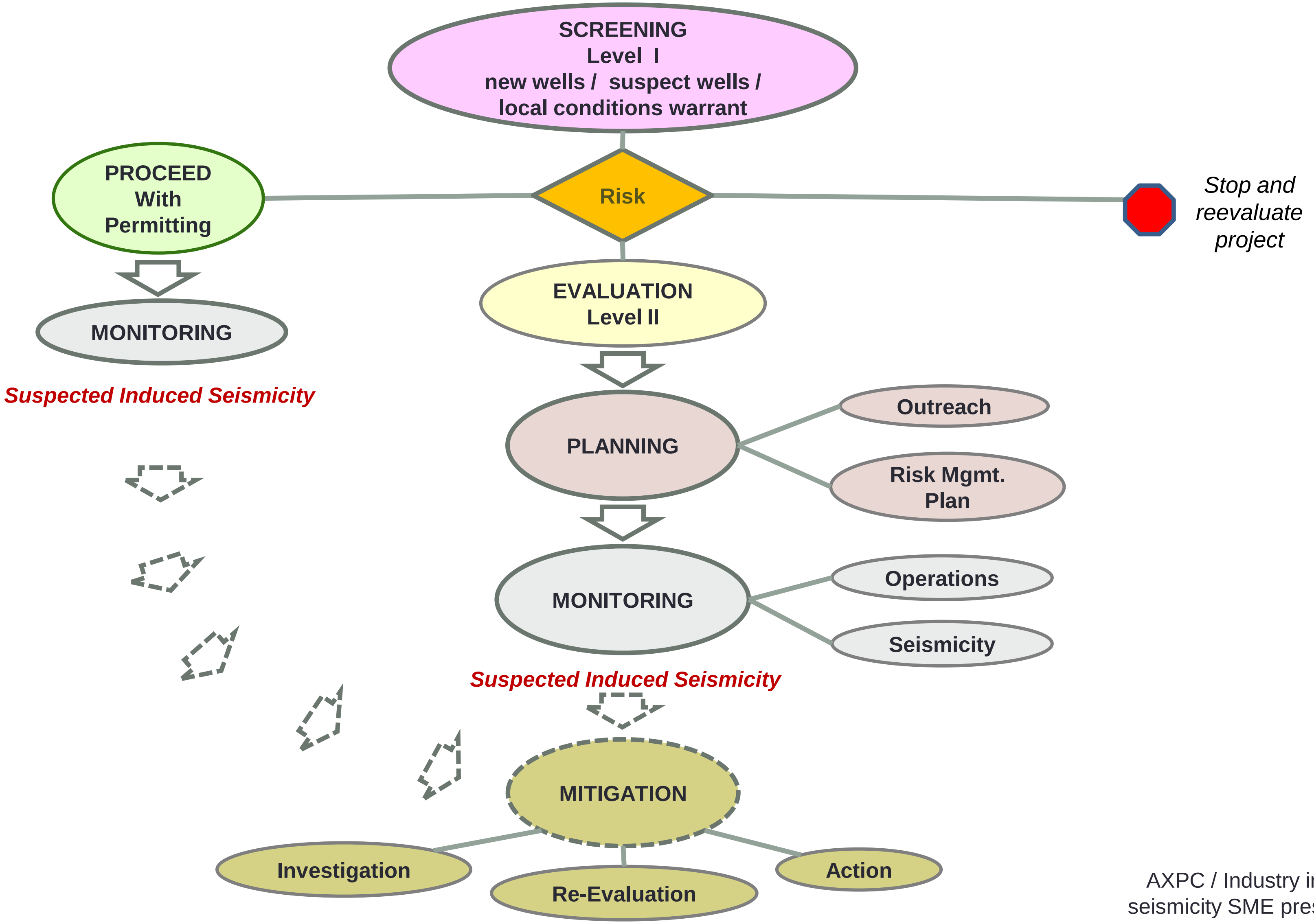
- Data, resources and tools for **Monitoring** evaluation

Item		Data, Resources and Tools
Operations	Fluid parameters	• Continuous monitoring and recording of injection rates, and pressures. • Daily and cumulative injection volumes measured and recorded. • Injectant properties noted: e.g. salinity, chemistry.
	Reservoir	• Fluid levels, shut-in pressure, pore pressure, changes in conditions. • Pressure transient behavior – e.g. falloff, step rate tests • Well performance and reservoir flow behavior (Hall plots, Silin plot) Storage/transmissivity
Seismicity	Regional	• Establish baseline conditions from USGS and other regional sources. • Maintain catalog of events from USGS and other regional sources. • Identify excursions from historical trends (temporal and spatial). • Note surface effects from seismic events recorded.
	Local	• (Level II) Install local array sufficient to locate events in the subsurface near the injection zone. • (Level II) Deploy sensors capable of measuring peak ground acceleration and velocity in the vicinity of the injection site. • Monitor possible "traffic light" events within 10 miles of well. • Evaluate whether any observed seismic events are induced or naturally occurring. • Report potentially induced threshold events established in the Risk Management plan that initiate mitigation steps.

** Toolbox contains various scalable tools user can select to fit for purpose*

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



AXPC / Industry induced seismicity SME presentation

Risk Mitigation

- **If, <u>and only if,</u>** induced seismicity suspected
- **<u>And</u>** if surface motions exceed thresholds: amber/red traffic light
- Goal is to manage and continue operations safely

<u>Investigation - steps</u>

1. Characterize event – magnitude, location, depth
2. Assess surface effects – motion, impact (distress, damage)
3. Calibrate seismicity to operations
4. Re-visit subsurface data – faults?
5. Improve monitoring

<u>Action</u>

1. Take steps defined in Risk Management Plan ("Traffic Lights")
2. Expand data gathering, monitoring, and analysis
3. Implement outreach plan
4. As necessary modify injection parameters

<u>Re-evaluation - steps</u>

1. Refresh evaluation – re-analyze
2. Analyze impact – ground motion studies, damage
3. Perform geomechanical and hydrologic analysis & modeling
   - Fault, stress, connection route of fluids
   - Pore pressure analysis
4. Explore all possible causes – e.g. geothermal, meteorological, production, volcanic
5. Catalog findings to inform mitigation actions

As necessary, utilize evaluation tool boxes

SUMMARY

- Induced seismicity is seismicity due to human activity
- Induced seismicity risk from hydraulic fracturing is negligible
- Induced seismicity from fluid disposal has occurred in very few, isolated cases
- Appropriate measurement of seismicity is local ground motion and its intensity
- The risk of induced seismicity from fluid disposal can be managed within a fit for purpose framework

Technical Elements to Consider in a Risk Management Framework for Induced Seismicity

Presentation to

2013 Underwater Injection Control Conference

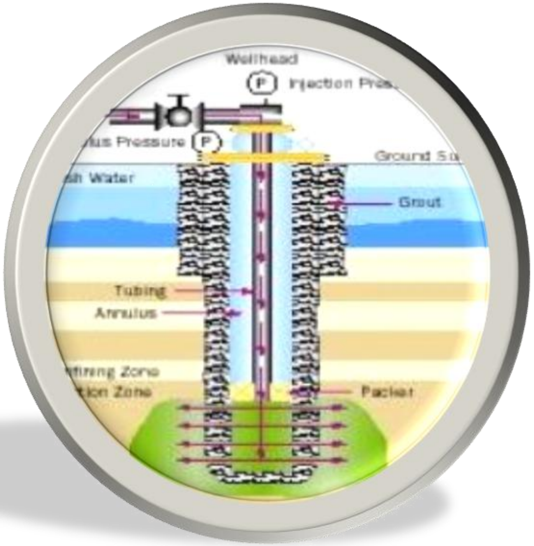
Ground Water Protection Council

by

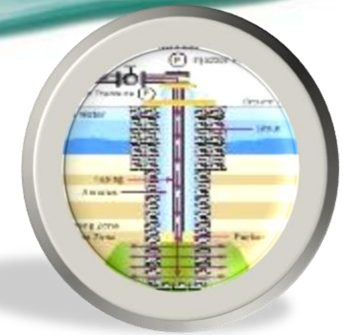
Adel H. Younan

Senior Structural & Civil Consultant

January 23rd, 2013



ExxonMobil
Upstream Research



Background

- Seismicity can be induced or triggered when stress or pore pressure changes promote slip along a fault.
- Theses changes can be due to:
  - Geothermal energy
  - Carbon Capture Storage
  - Mining
  - Dam/reservoir impoundment
  - Waste water disposal wells
  - O&G injection/extraction
  - Hydraulic fracturing

NATIONAL ACADEMY OF SCIENCES

NAS has recently examined induced seismicity across multiple energy sectors. Three major findings were published from this study (1):

1. "The process of hydraulic fracturing a well as presently implemented for shale gas recover does not pose a high risk for inducing felt seismic events
2. Injection of disposal of waste water derived from energy technologies into the subsurface does pose some risk for induced seismicity, but very few events have been documented over the past several decades relative to the large number of disposal wells in operation; and
3. CCS, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events."

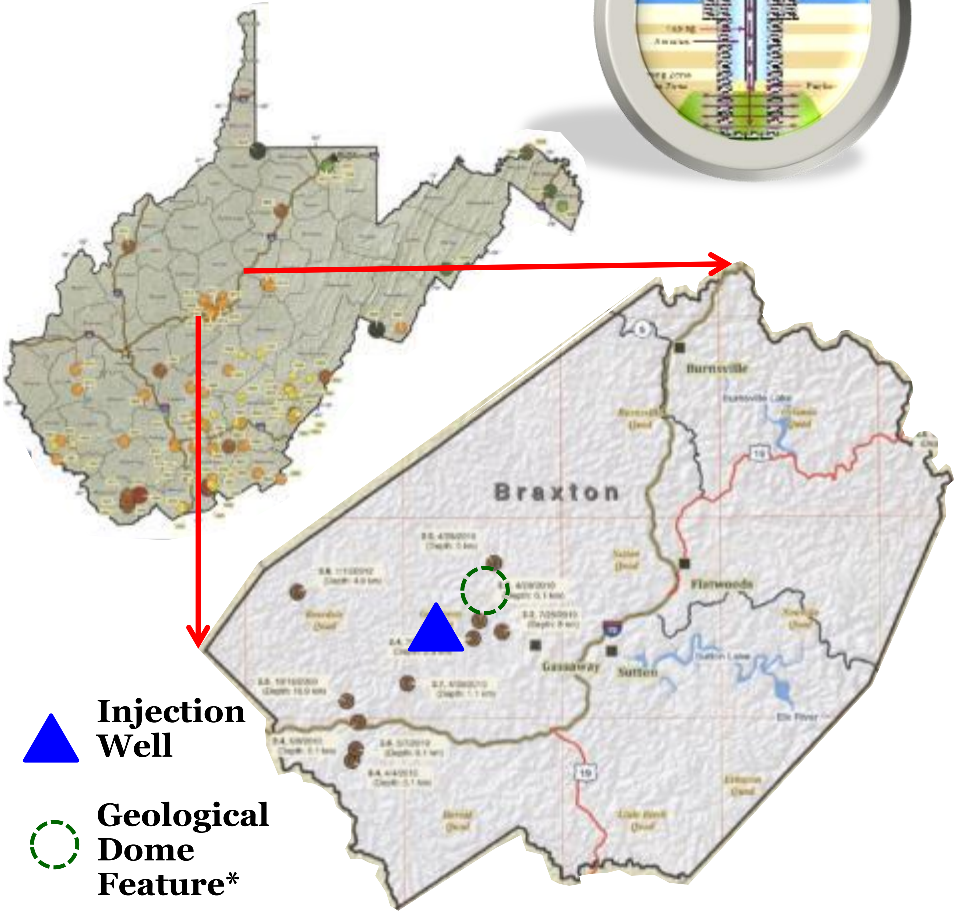
(1) NAS (June 2012), "Induced Seismicity Potential in Energy Technologies", http://www.nap.edu/catalog.php?record_id=13355

Case Studies

Industry Data

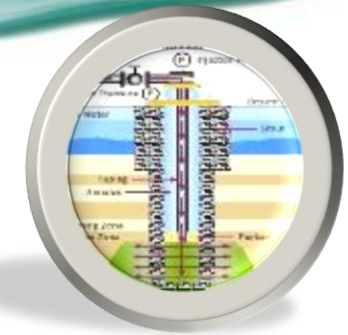
1. DFW – Airport (Disposal)
2. DFW – Cleburne (Disposal)
3. Braxton WV (Disposal)
4. Arkansas (Disposal)
5. General Case of Injection Wells
6. Horn River Basin
   a) Etsho
   b) Tattoo
7. U.K. Bowland Shale
8. General HF Wells:

   microseisms always created



Seismic Epicenters of West Virginia (1824-2012) & Braxton County (2000-2012). (Images from West Virginia Geological and Economic Survey)

ExxonMobil
Upstream Research



Shaking Impact

Primary Structure

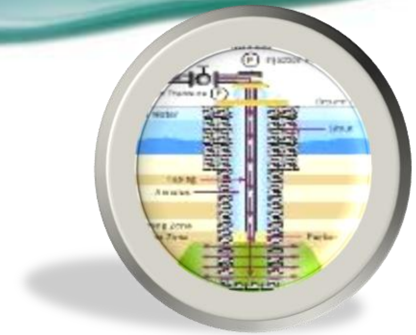
- Design is fundamentally based on probabilistic seismic analysis defined by a hazard curve:
  - This defines the probability of exceeding a spectral acceleration at a specified structural period;
  - Analysis is based on seismic sources with associated activities probabilistically defined;
  - Lower limit of earthquakes < M4
- Induced seismicity, typically below M4, is likely to have little to no impact on primary structure

Humans & Secondary Components

- Likely to be more sensitive to small tremors
- Highly dependent on
  - Local soil conditions ; and
  - In-structure local motion amplification
- Best monitored via surface acceleration, e.g. Modified Mercalli Intensity (MMI)

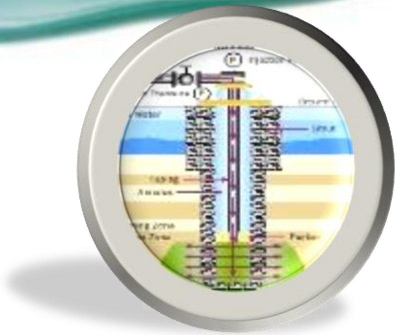
MMI	Magnitude	Acc. (g)	Description of Intensity Level
I	1.0-3.0	<0.0017	Not felt except by a very few under especially favorable circumstances.
II	3.0-3.9	0.0017	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	4.0-4.9	0.014	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an arthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV	5.0-5.9	0.014-0.039	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably
V	6.0-6.9	0.039-0.092	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	7.0 and higher	0.092-0.18	Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	7.0 and higher	0.18-0.34	Damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars.
VIII	7.0 and higher	0.34-0.65	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	7.0 and higher	0.65-1.24	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X		>1.24	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI		>1.24	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII		>1.24	Damage total. Lines of sight and level distorted. Objects thrown into the air.

Risk Management



- Risk is the combination of Probabilities and Consequences
- A standard tool used in risk assessment is a risk matrix approach to identify the risk level
- With risk level identified, possible risk mitigation approaches can be evaluated (effectiveness / cost)

HIGH	MEDIUM	LOW	VERY LOW
Consider suspending operations; mitigate to reduce risk	Adjust operations; consider steps to mitigate risk	Operations continue as normal	Operations continue as normal



Risk Management

- Risk is the combination of Probabilities and Consequences
- A standard tool used in risk assessment is a risk matrix approach to identify the risk level
- With risk level identified, possible risk mitigation approaches can be evaluated (effectiveness / cost)

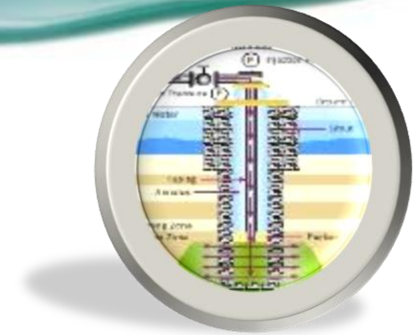
Probability

Consequence

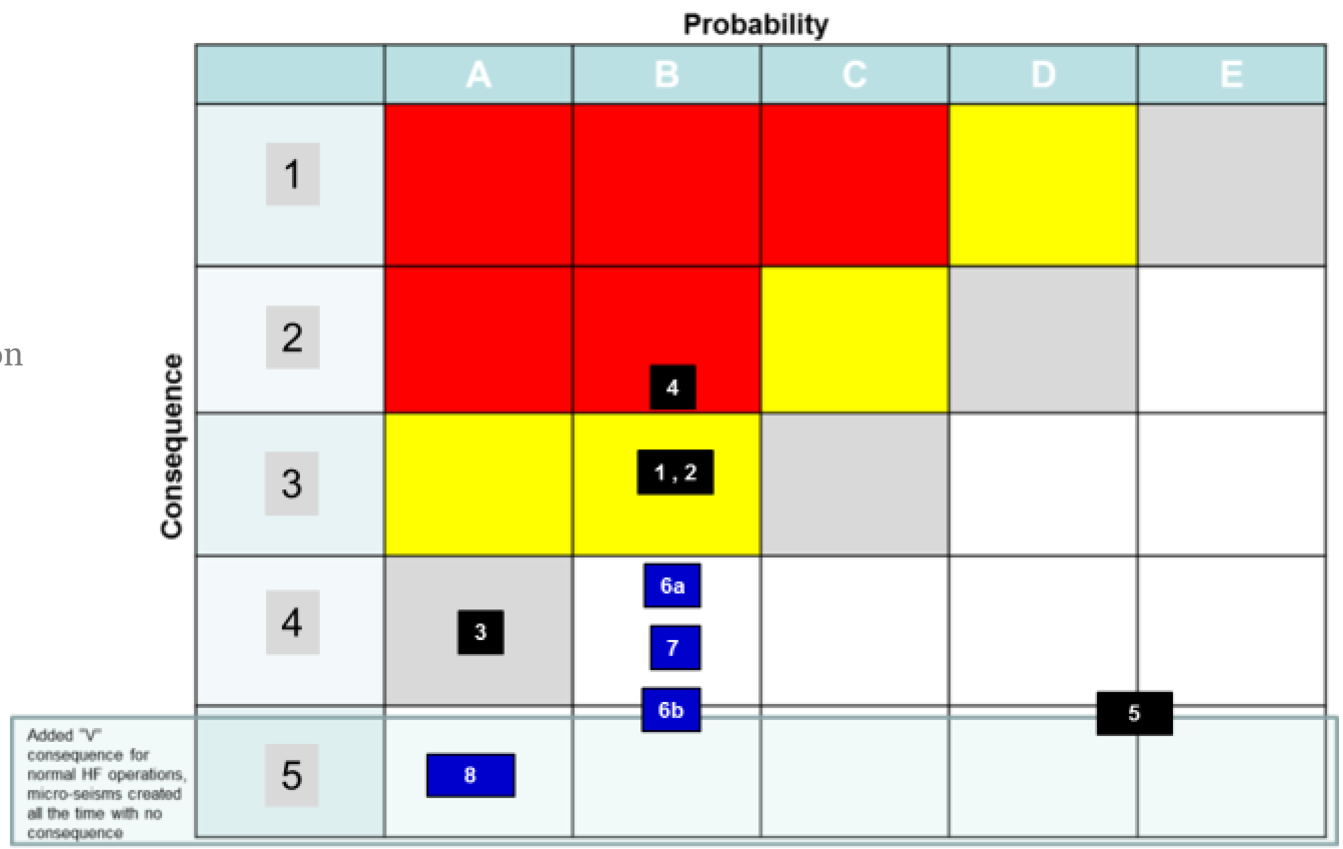
		A	B	C	D	E
	1	HIGH	HIGH	HIGH	MEDIUM	LOW
	2	HIGH	HIGH	MEDIUM	LOW	VERY LOW
	3	MEDIUM	MEDIUM	LOW	VERY LOW	VERY LOW
	4	LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW
Added "V" consequence for normal HF operations, micro-seisms created all the time with no consequence	5	VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW

ExxonMobil
Upstream Research

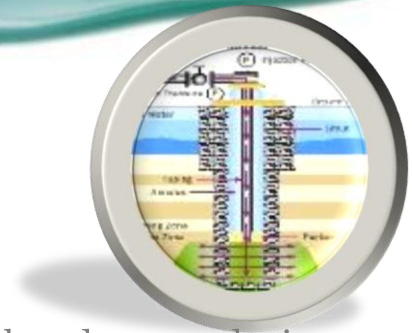
Risk Management



1. DFW – Airport (Disposal)
2. DFW – Cleburne (Disposal)
3. Braxton WV (Disposal)
4. Arkansas (Disposal)
5. General Case of Injection Wells
6. Horn River Basin
   a) Etsho
   b) Tattoo
7. U.K. Bowland Shale
8. General HF Wells: microseisms always created)



ExxonMobil
Upstream Research



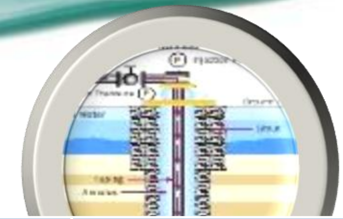
Perspective

- Approaches to assess and manage seismicity risk should be encouraged, should be based on sound science, and take into account the local conditions, operational scope, geological setting, historical baseline seismicity levels; and reflect reasonable and prudent consideration of engineering standards and codes related to seismicity structural health.
- Seismicity monitoring and mitigation should be considered in local areas where induced seismicity is of significant risk, such as in areas where:
  - a) significant seismicity (above historical baseline levels) has actually occurred and sound technical assessment indicates that the seismicity is associated with fluid injection operations, or
  - b) if sound technical assessment indicates the local area may possess significant risk associated with potential induced seismicity.
- In local areas where induced seismicity is of significant risk, appropriate monitoring and mitigation should include:
  - a) a mechanism to alert the operator in near real-time to the occurrence of seismicity significantly above local historical baseline levels, and
  - b) a procedure to modify and/or suspend operations if seismicity levels increase above threshold values for maintaining local structural health integrity and minimizing secondary damage

ExxonMobil
Upstream Research

Back Up

Probability Considerations



Probability	Fluid Volume	Formation Characteristics	Tectonic / Faulting / Soil Conditions	Operating Experience	Public Sensitivity & Tolerance	Local Construction Standards
A Very Likely	Large volumes of injection in immediate or close proximity to active faults	Deeper injection horizon; highly consolidated formations	Large-scale developed/active faults are present at depths that could be influenced by pressure / fluid communication associated with injection; strongly consolidated formation; soil conditions amplify vibrational modes	Past injection experience in region with damaging levels of ground shaking	High population density & historically low background seismicity	Primitive construction and limited/no engineering applied for earthquake resistant designs
B Somewhat Likely	Large or moderate volumes of fluid injected in proximity to active faults	Moderate depth injection horizons; highly consolidated formations	Large-scale developed/active faults may possibly be present, but not identified; strongly consolidated formation, soil conditions may amplify vibrational modes	Limited injection experience historically in region	Moderate / high population density and/or historically low / moderate background seismicity	Sound construction practices, but age/vintage of building construction pre-dates earthquake engineering design principles.
C Unlikely	Moderate fluid volume of injection; remote from any active fault	Shallow injection horizon; highly consolidated formations	Faults well identified, and unlikely to be in influenced by pressure / fluid associated with injection; moderately consolidated formation	Significant injection experience historically in region with no damaging levels of ground shaking	Moderate population density and historically moderate / high background seismicity	Ground vibration and seismic activity routinely considered in civil / structural designs and routinely implemented in majority of buildings
D Very Unlikely	Small fluid volume of injection; remote from any active fault	Shallow injection horizon; weakly consolidated formations	Stable stress environment; minimal faulting; if faults present, too small to induce any surface felt seismicity; weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	Significant injection experience historically in region with no surface felt ground shaking	Low population density & historically moderate background seismicity	Rigorous earthquake engineering civil / structural designs routinely implemented and required
E Very Highly Unlikely	Small fluid volume of injection; remote from any active faults	Shallow injection horizon, Poorly consolidated formations	Stable stress environment; no significant faults, weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	Significant injection experience historically across wide geographic region with no surface felt ground shaking	Low population density & historically high background seismicity	Rigorous earthquake engineering civil / structural designs routinely implemented and required

Consequence Considerations

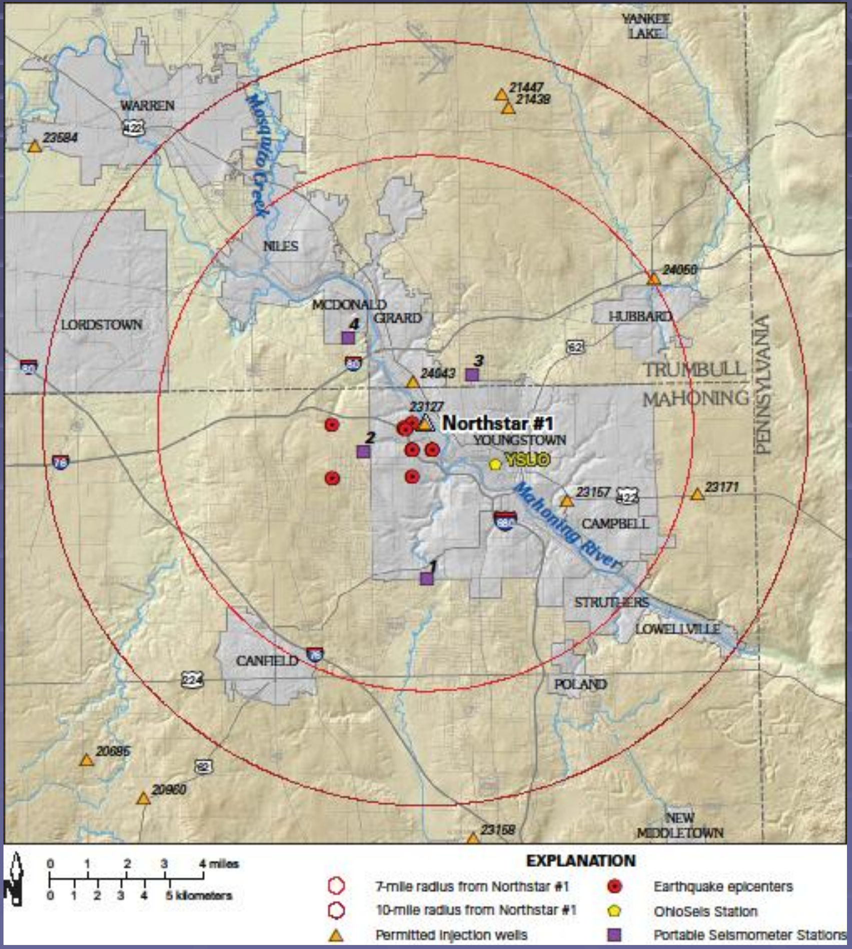
Consequence Considerations	Safety / Health Impact	Environmental Impact	Public Impact	Financial Impact
1 *(MMI: > VIII)*	Fatalities and serious injuries; building structural damage.	Potential widespread long-term significant adverse affects. Release of potentially hazardous compounds – extended duration &/or large volumes in affected area (large chemical static / transport vessels and pipelines break).	Ground shaking felt in large region. Extensive mobilization of emergency 1st responders. Disruption of community services for extended time.	$$$$
2 *(MMI: VI - VII)*	Serious injuries; building cosmetic & secondary building content damage.	Potential localized medium term significant adverse effects. Release of potentially hazardous compounds short-duration &/or limited volumes (large vessels break).	Ground shaking felt by all in local area. Mobilization of emergency 1st responders. Disruption of community services for brief time.	$$$
3 *(MMI: V – VI)*	Minor injuries in isolated circumstances; building secondary content damage.	Release of potentially hazardous compounds in limited volumes (e.g., containers break).	Ground shaking felt by sensitive few at site. Limited site impact and limited mobilization of 1st responder(s).	$$
4 *(MMI: IV – V)*	First aid in isolated circumstances; isolated secondary building content damage.	Release of potentially hazardous compounds in very small volumes (e.g., small containers break).	Minor public complaints.	$
5 *(MMI: I – IV)*	None	None	None	None

OHIO'S NEW CLASS II REGULATIONS AND ITS PROACTIVE APPROACH TO SEISMIC MONITORING AND INDUCED SEISMICITY

Tom Tomastik, ODNR, Division of Oil and Gas Resources Management

THE YOUNGSTOWN EVENT

- On December 31,2011 a 4.0 magnitude seismic event occurred near the Class II Northstar #1 injection well in Youngstown, Ohio
- Caused immediate changes to the Class II saltwater injection well program
- Shutdown three other Class II wells and one Class II permit in a seven mile radius around the Northstar #1
- Put a hold on the issuance of any new permits
- A preliminary report on the Youngstown seismic events was released in March of 2012



THE AFTERMATH

- Due to these seismic events, the Director of Ohio DNR and the Governor initiated drafting of new regulations to help prevent larger magnitude induced seismicity associated with Class II injection
- Regulations to be based upon sound scientific methods
- Development of regulations that are evaluated and implemented on a well-by-well basis

DRAFT REGULATIONS

- The drafting of new Class II SWD regulations started in late spring of 2012
- On July 10, 2012, the Governor issued Executive Order 2012-09K as an emergency amendment of UIC Rules 1501:9-3-06 and 1501:9-3-07 of the Ohio Administrative Code
- This Executive Order allowed for the implementation of new draft UIC rules into the legislative process.

NEW CLASS II REGULATIONS

- The new UIC Class II saltwater injection well rules proceeded through the legislative process, were passed and went into effect on October 1, 2012
- The Division of Oil and Gas Resources Management started again to issue new Class II saltwater injection well permits in November of 2012
- These new permits had the new regulations added as conditions to those permits
- The new regulations are added to a permit on a well-by-well evaluation basis – "The chief may require the following tests or evaluations of a proposed brine injection well, in any combination that the chief deems necessary."

POTENTIAL TESTS OR EVALUATIONS

- Pressure fall-off testing
- Geological investigation of potential faulting within the immediate vicinity of the proposed injection – may require seismic surveys or other methods
- Submittal of a seismic monitoring plan
- Testing and recording of original bottomhole injection interval pressure
- Minimum geophysical logging suite – gamma ray, compensated density-neutron, and resistivity logs
- Radioactive tracer or spinner survey
- Prohibits drilling into the Precambrian basement
- Any such other tests the chief deems necessary

ADDITIONAL AUTHORITY

- If tests or evaluations are required, applicant shall refrain from injection until evaluation of results are performed
- Chief has the right to withhold injection authority or to require well plugged after results are evaluated
- Chief may implement a graduated maximum allowable injection pressure based upon the data from the tests or evaluations

OTHER REGULATORY CHANGES

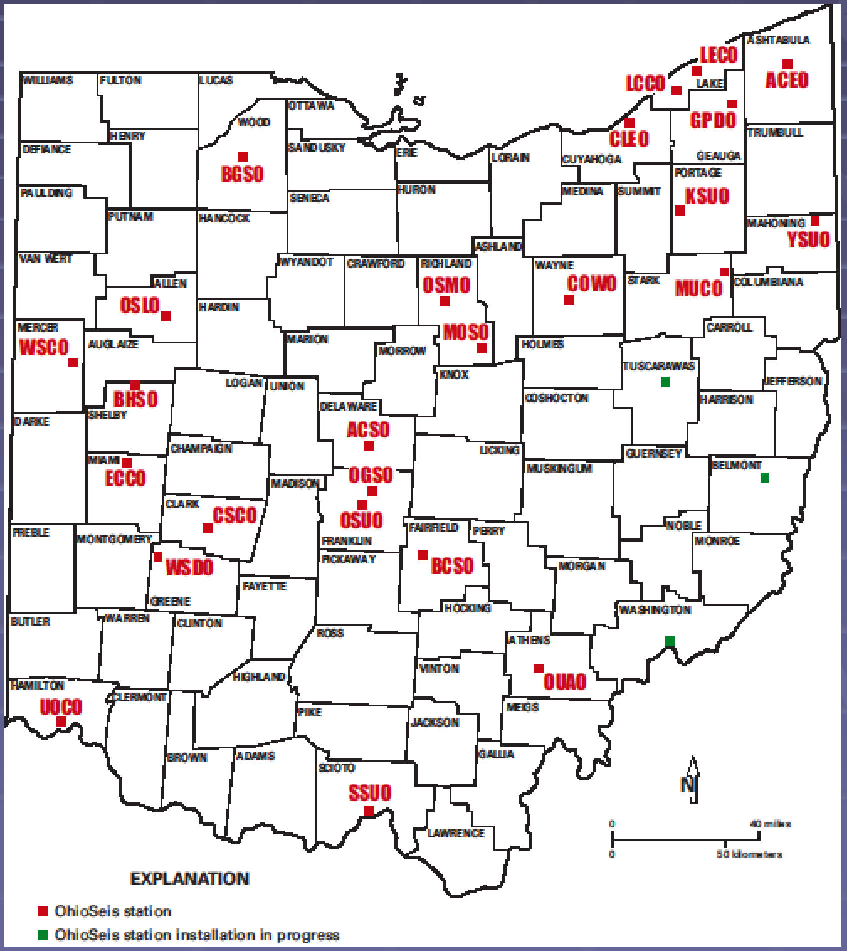
- Increased one-day public notice requirement to a five-day public notice requirement
- All new Class II injection wells must continuously monitor the injection and annulus pressures to maintain mechanical integrity
- Must have a shut-off device installed on the injection pump set to the maximum allowable injection pressure

SEISMIC MONITORING

- During the development of the new UIC regulations, it became apparent to the Ohio Division of Oil and Gas Resources Management there was a need for a better understanding of seismicity issues in Ohio
- Two new geologists were hired in early summer of 2012 to work in the Division's UIC program and one had a PhD in seismology which will further strengthen the Division's ability to evaluate seismic events and to design seismic monitoring plans if needed
- Additionally, the decision was made by the chief for the Division to proactively start our own seismic monitoring for microseismic events around a few of the new Class II injection well sites

CURRENT SEISMIC MONITORING IN OHIO

- The Ohio Seismic Network (OhioSeis) consists of 29 cooperative, volunteer-operated seismic stations at colleges, universities, and other institutions across Ohio
- Network is managed by the Ohio Division of Geological Survey
- The first stations of OhioSeis went on-line in January of 1999
- Prior to 1999, there was only one seismic station in Ohio



ISSUES WITH OHIOSEIS

- Regional seismic networks such as OhioSeis rely upon a single-component system
- Most of the stations in the OhioSeis network are one-component (vertical) stations and are only capable of recording the up and down motion of a seismic event
- This dramatically reduces the accuracy in calculation of surface location and depth of a seismic event
- The Ohio Division of Geological Survey has a very limited budget to run the OhioSeis network

EXAMPLE OF OHIOSEIS NETWORK STATION

PROACTIVE SEISMIC MONITORING

- The Division's proactive approach to seismic is to purchase three-component portable seismic stations and install these stations around newly permitted Class II injection wells to initiate seismic monitoring in advance of start-up of injection operations

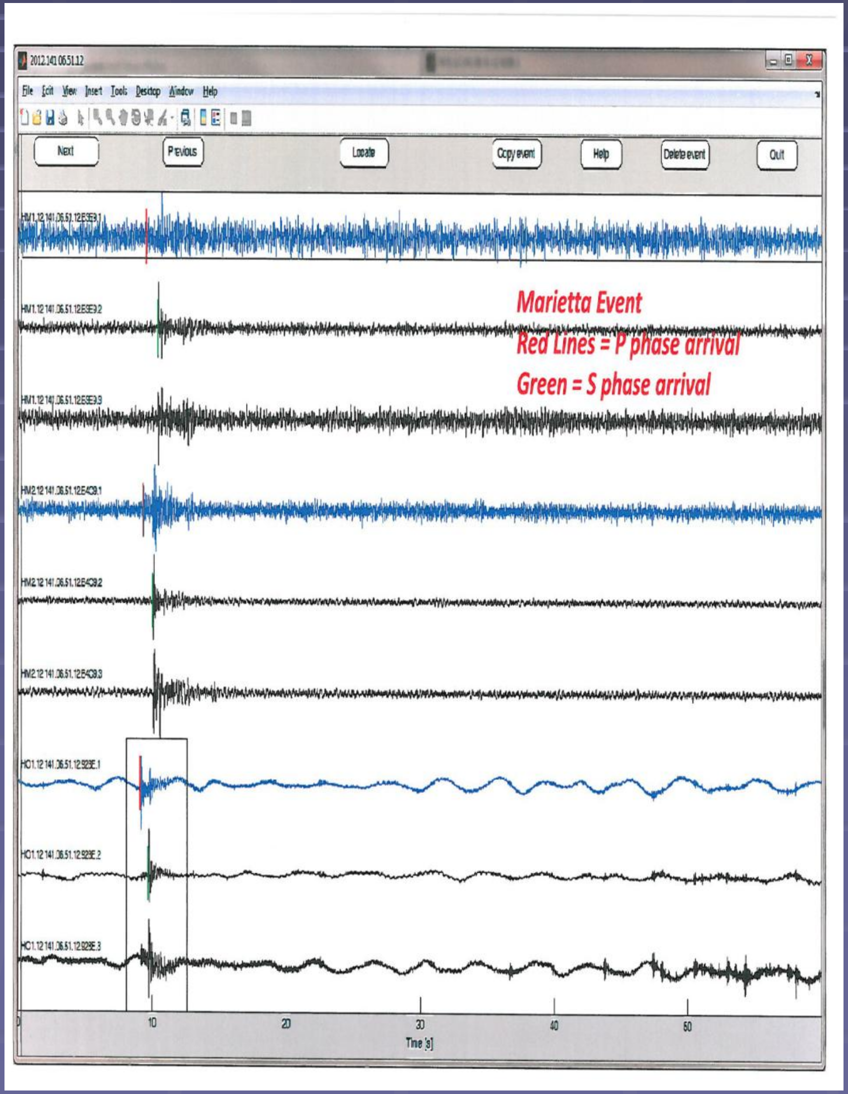
THREE COMPONENT STATIONS

- Capable of recording data on the X, Y, and Z axes
- One sensor detects vertical motion (up/down) and two sensors detect horizontal motion in the north-south and east-west directions
- This type of station also measures the body and surface waves, thus providing information on the depth and strength of a seismic event

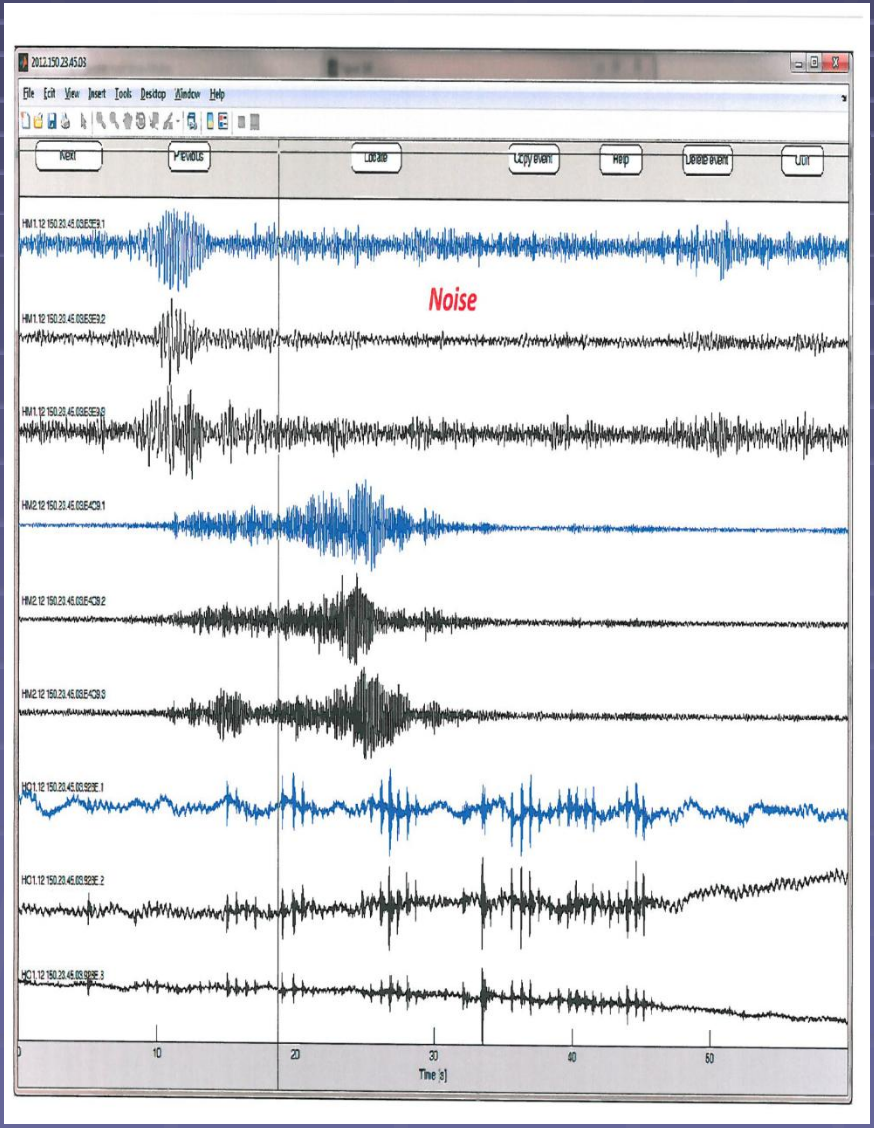
PORTABLE SEISMIC STATIONS

- To date, the Division has purchased nine RefTek three-channel digitizers and nine Sercel, Inc. three-directional L-22 sensors
- L-22 sensors have a range of 0.1 to 1000 hertz with a natural frequency of 2 hertz
- Three of each have been deployed into the field
- Awaiting the arrival of the six remaining units
- Potential to purchase 11 more units

EXAMPLE OF A SEISMIC EVENT

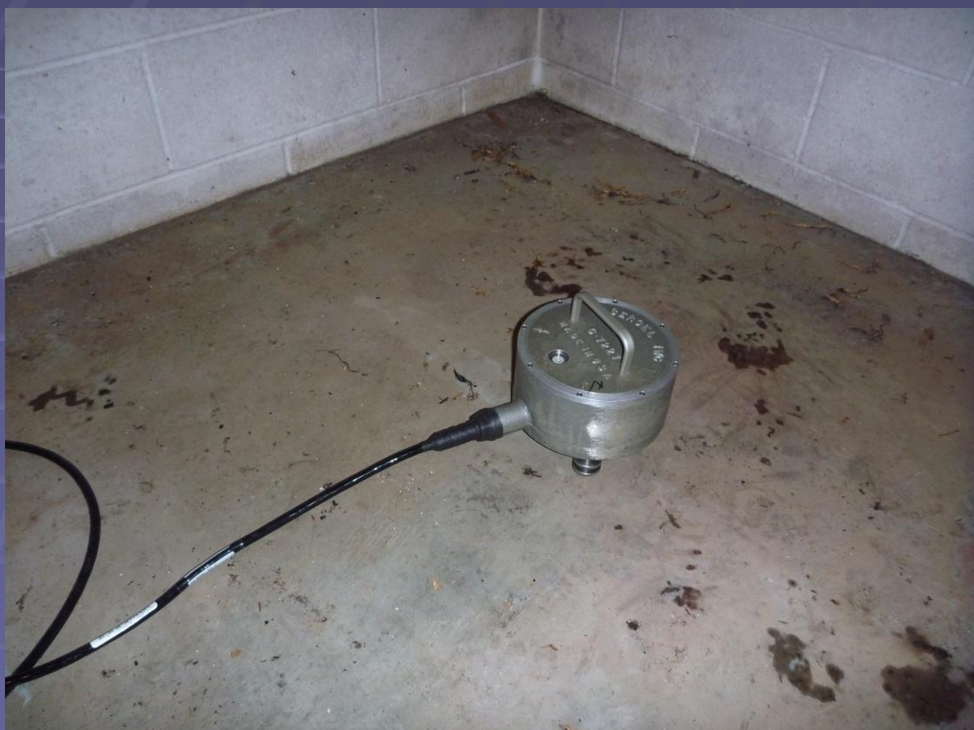


EXAMPLE OF NOISE



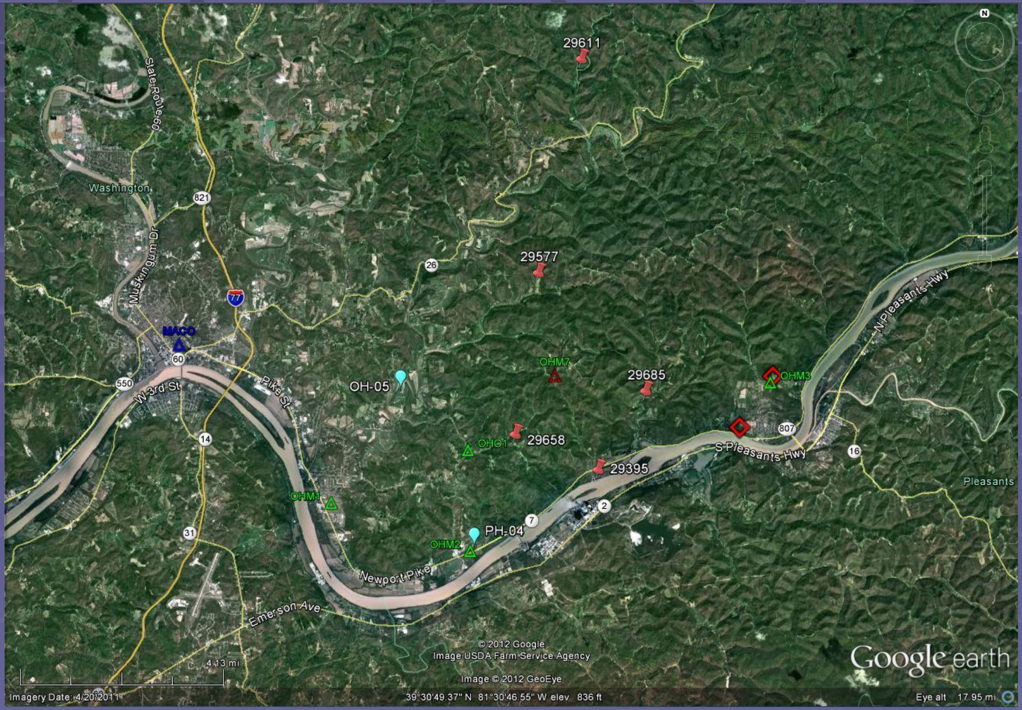
REFTEK DIGITIZER

SERCEL INC. L-22 SENSOR



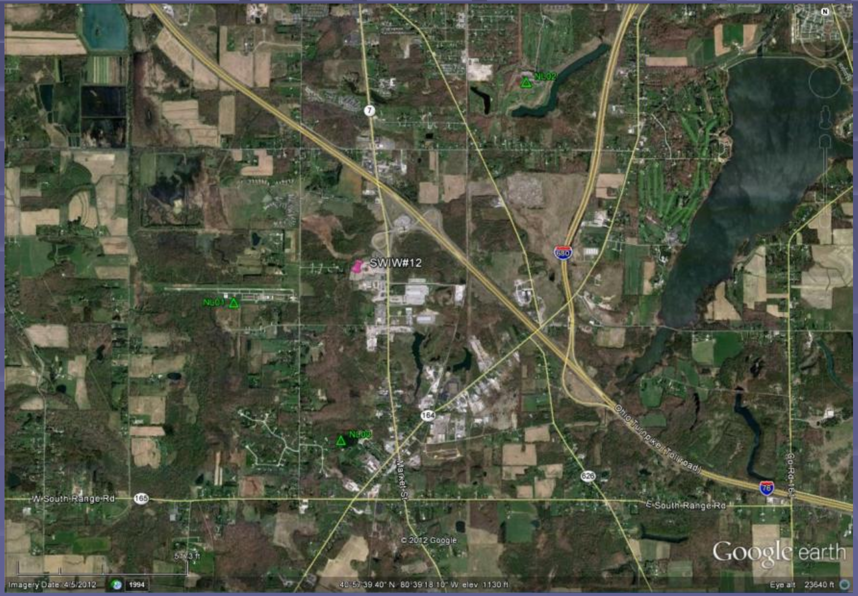
SOUTHEASTERN OHIO STATION DEPLOYMENT

- Deployment of one station in conjunction with existing Ohio Division of Geological Survey portable stations around Marietta, Ohio
- Monitoring of existing Class II operations and two newly permitted Class II wells not in operation yet



NORTHEASTERN OHIO STATION DEPLOYMENT

- Two stations deployed around a newly drilled Class II injection well 12 miles south of Youngstown, Ohio near North Lima
- New unit will be deployed to the third station when received



NORTH LIMA PORTABLE STATIONS

- Installation of the two portable units at North Lima were installed approximately three feet below the ground
- Sensor installed on poured concrete pad with digitizer and battery for solar panel

STATION INSTALLATION

FINISHING INSTALLATION

CURRENT STATUS OF PORTABLE SEISMIC NETWORK

- Once the new units are received, portable stations will be installed in ground also
- Currently all stations are running on electric power, but solar panels have been purchased for use
- Currently, five wireless modems have been installed – three in southeastern Ohio and two in North Lima
- Real time monitoring of all five stations has started
- Goal is to get three portable stations around each Class II injection facility

REAL TIME MONITORING

DIVISION'S PROACTIVE APPROACH TO SEISMIC MONITORING

- The Division is placing portable seismic stations around Class II injection wells and start monitoring prior to commencement of injection operations
- Continue to monitor for microseismic events up to approximately six months after initiation of injection operations
- If no evidence of larger seismic events, move portable seismic stations to another Class II location

RECOMMENDATIONS

- As scientists, we need to stop making the statement that this "area has not had any previous seismic activity"
- Clarify what are microseismic events and what can cause them
- Be cautious in using the term "earthquake" when in reality it is a microseismic event

CONCLUSIONS

- The Division will continue to proactively address seismic monitoring in relation to Class II injection
- The chief now has the authority to require seismic surveys, seismic monitoring, and other tests to address potential geologic conditions that may induce seismicity
- The results of any scientific data analysis are only as good as the quality and integrity of the recorded data set
- It is critical that we do good, sound scientific research before drawing conclusions that may not be based on reliable scientific methods

QUESTIONS?

WVDEP

Office of Oil & Gas

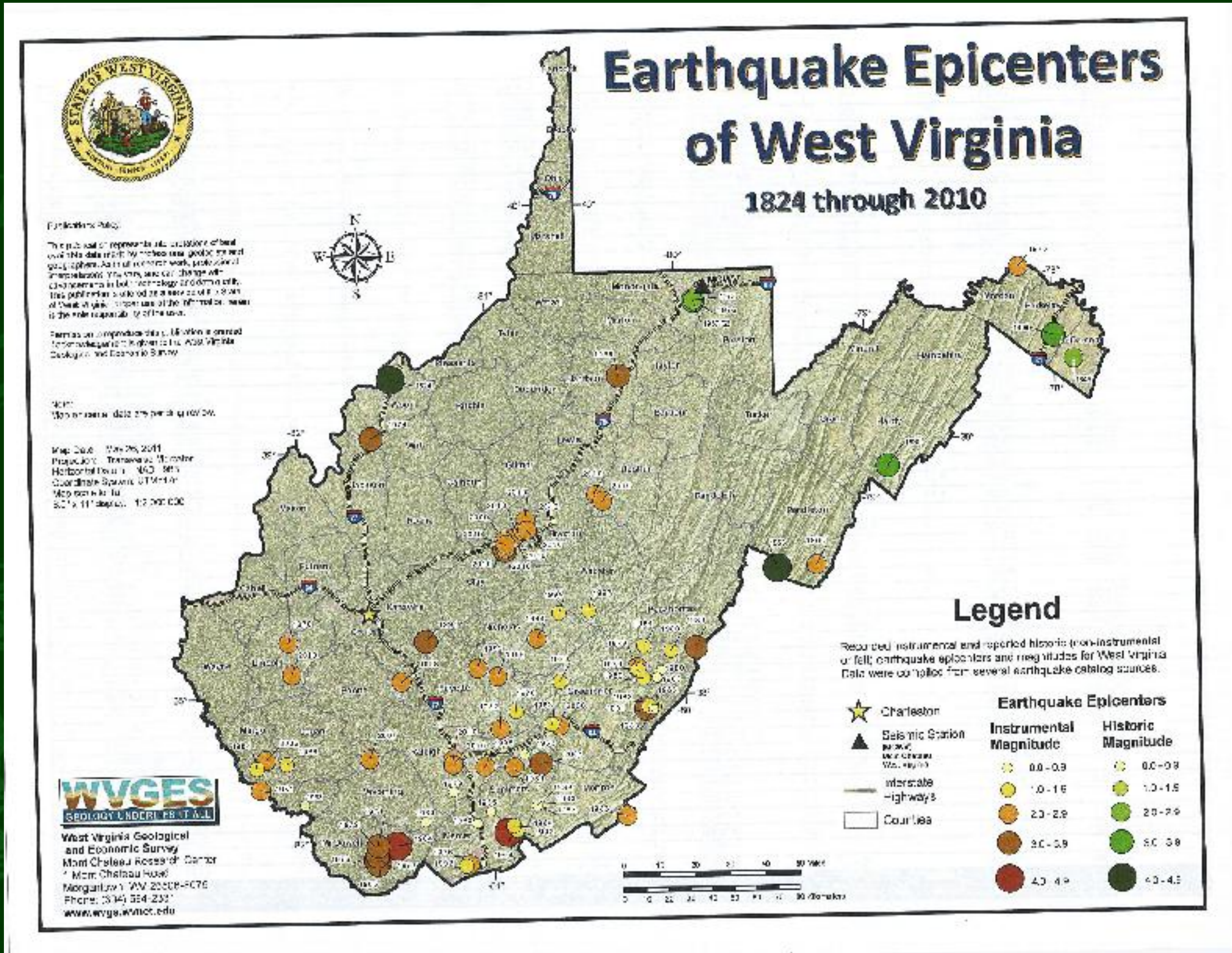
west virginia department of environmental protection

Promoting a Healthy Environment

UIC Disposal Wells

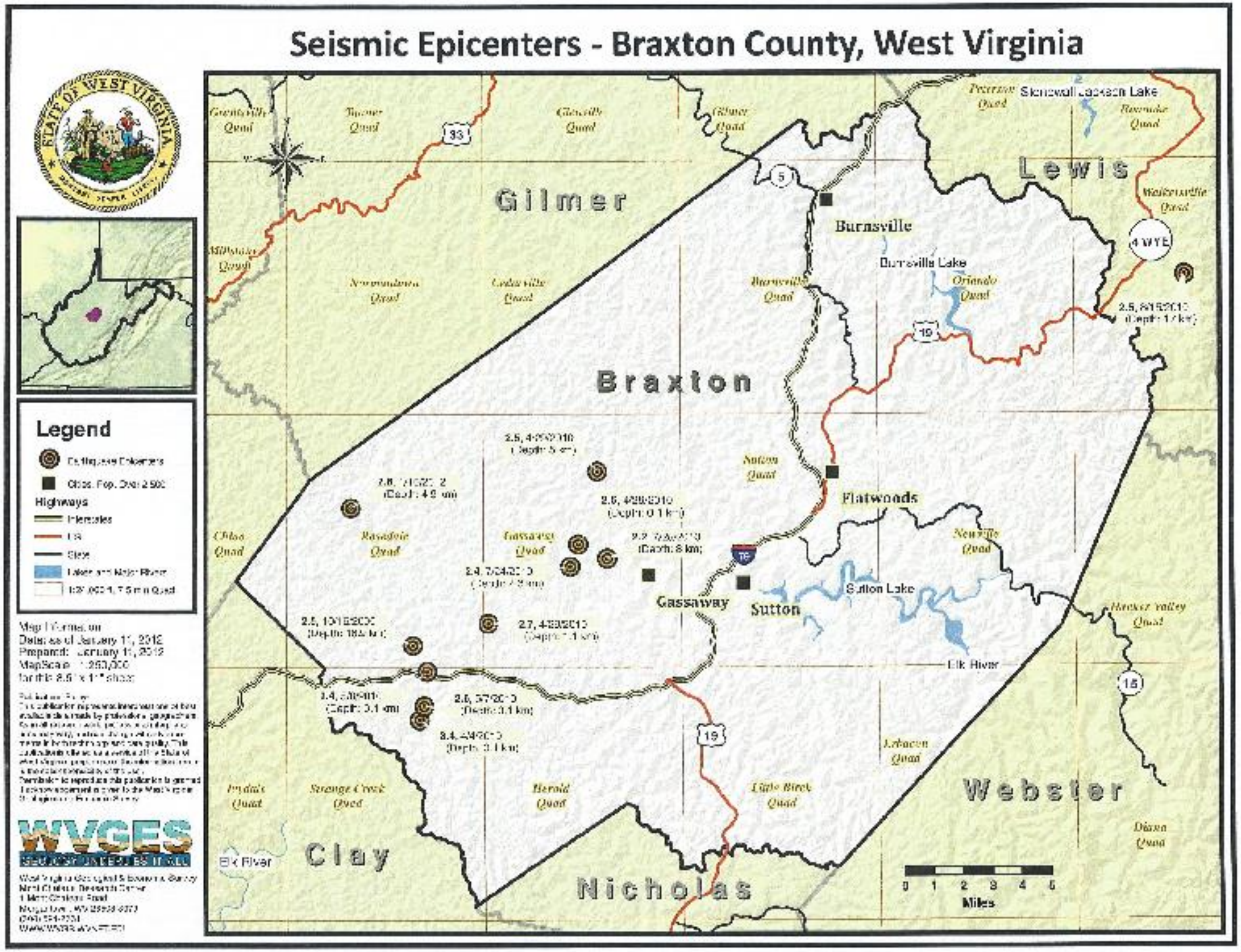
- 52 active non-commercial wells
- 14 active commercial wells

west virginia department of environmental protection
Promoting a Healthy Environment

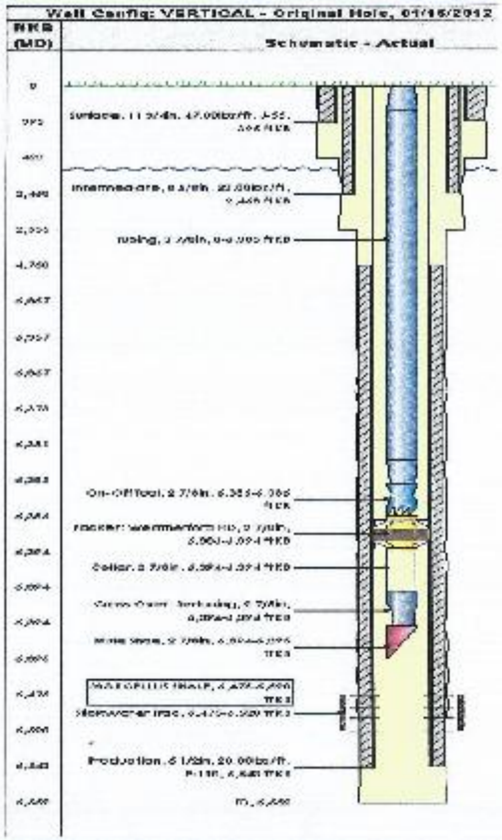

Earthquake Epicenters
of West Virginia
1824 through 2010
Legend
Recorded instrumental and reported historic (non-instrumental or felt) earthquake epicenters and magnitudes for West Virginia. Data were compiled from several earthquake catalog sources.
Charleston
Seismic Station
Interstate Highways
Counties
Earthquake Epicenters
Instrumental Magnitude
Historic Magnitude
0.0 - 0.9
1.0 - 1.9
2.0 - 2.9
3.0 - 3.9
4.0 - 4.9
WVGES
West Virginia Geological and Economic Survey
Mont Chateau Research Center
1 Mont Chateau Road
Morgantown, WV 26508-8079
Phone: (304) 594-2331
www.wvgs.wvnet.edu

UIC

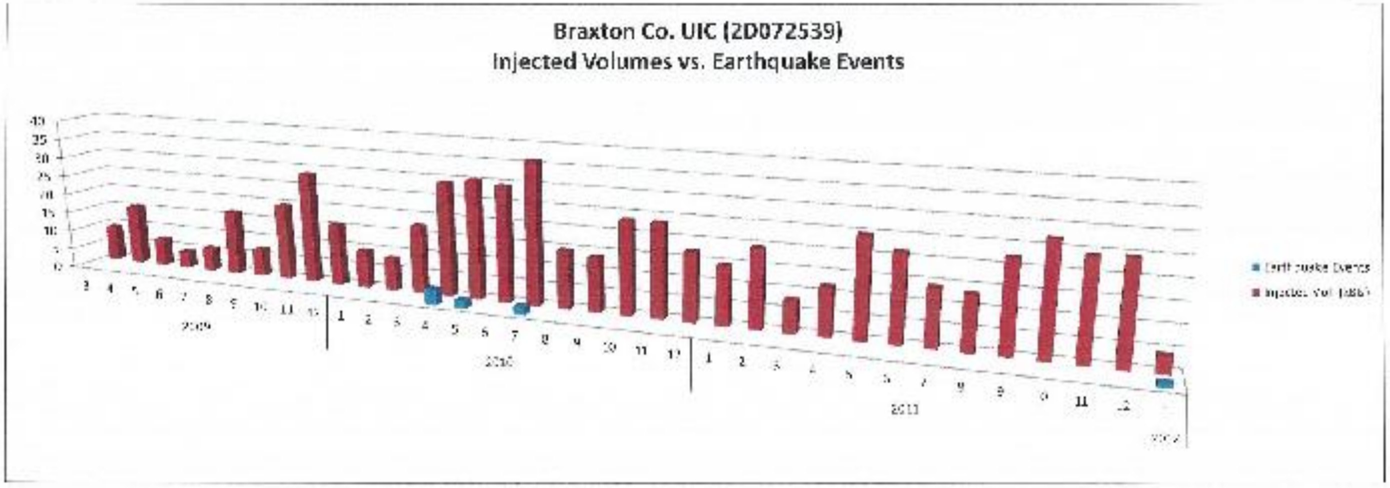
- 2010 there was multiple seismic events within Braxton County in central West Virginia.
- Initiating an evaluation of the UIC well within that area.

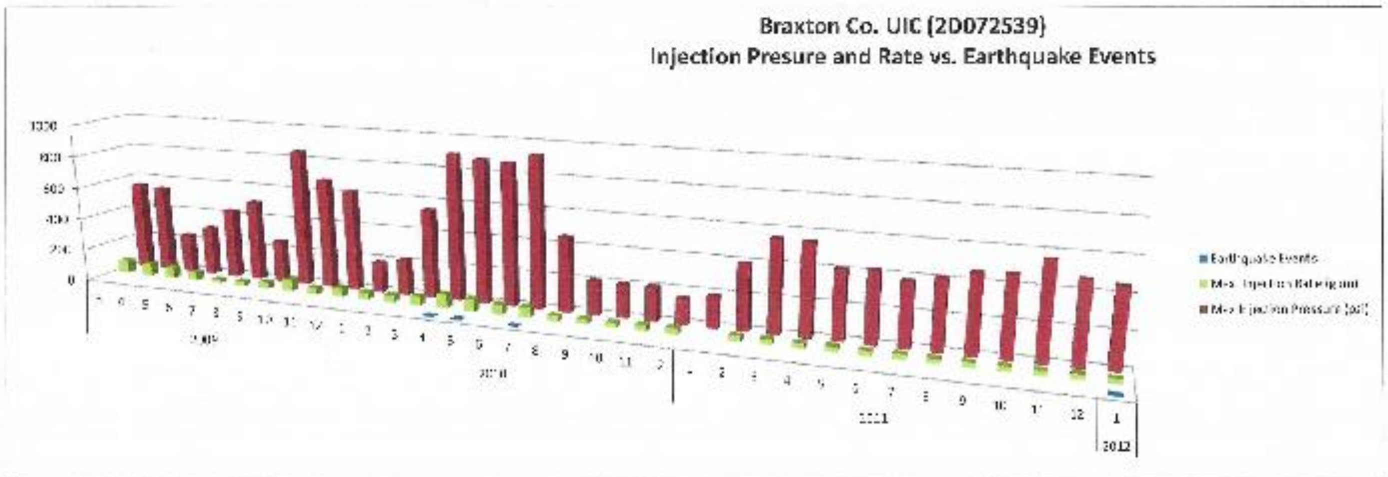

Seismic Epicenters - Braxton County, West Virginia
Gilmer
Lewis
Braxton
Webster
Clay
Nicholas
Burnsville
Burnsville Lake
Stonewall Jackson Lake
Flatwoods
Gassaway
Sutton
Sutton Lake
Elk River
Legend
Earthquake Epicenters
Cities Pop. Over 2,500
Highways
Interstates
US
State
Lakes and Major Rivers
2.5, 8/15/2010 (Depth: 1.7 km)
Miles
WVGES

Wellbore Diagram



- Well TD @ 6,552'
- Marcellus Shale 6,472'- 6,525'
- 180 Perforations 6,475'- 6,520'
- 11-3/4" Surface Csg set to 395'
- Cement to Surface
- 8-5/8" Intermediate Csg set to 2,468'
- Cement to Surface
- 5.5" 20 lb/ft P-110 Production Csg set to 6,543'
- Bonded Cement to 4,750'
- 2-7/8" tbg set @ 6,395' w/ WTF packer set @6,386'


Braxton Co. UIC (2D072539)
Injected Volumes vs. Earthquake Events


Braxton Co. UIC (2D072539)
Injection Presure and Rate vs. Earthquake Events
Earthquake Events
2012

UIC

Recently with interest in Marcellus development an increased interest has been placed on the permitting and disposal of fluids into commercial wells.

Conclusions

west virginia department of environmental protection

Promoting a Healthy Environment

Colorado Oil and Gas Conservation Commission

UNDERGROUND INJECTION CONTROL (UIC) SIESMICITY

STATE OF COLORADO OIL & GAS

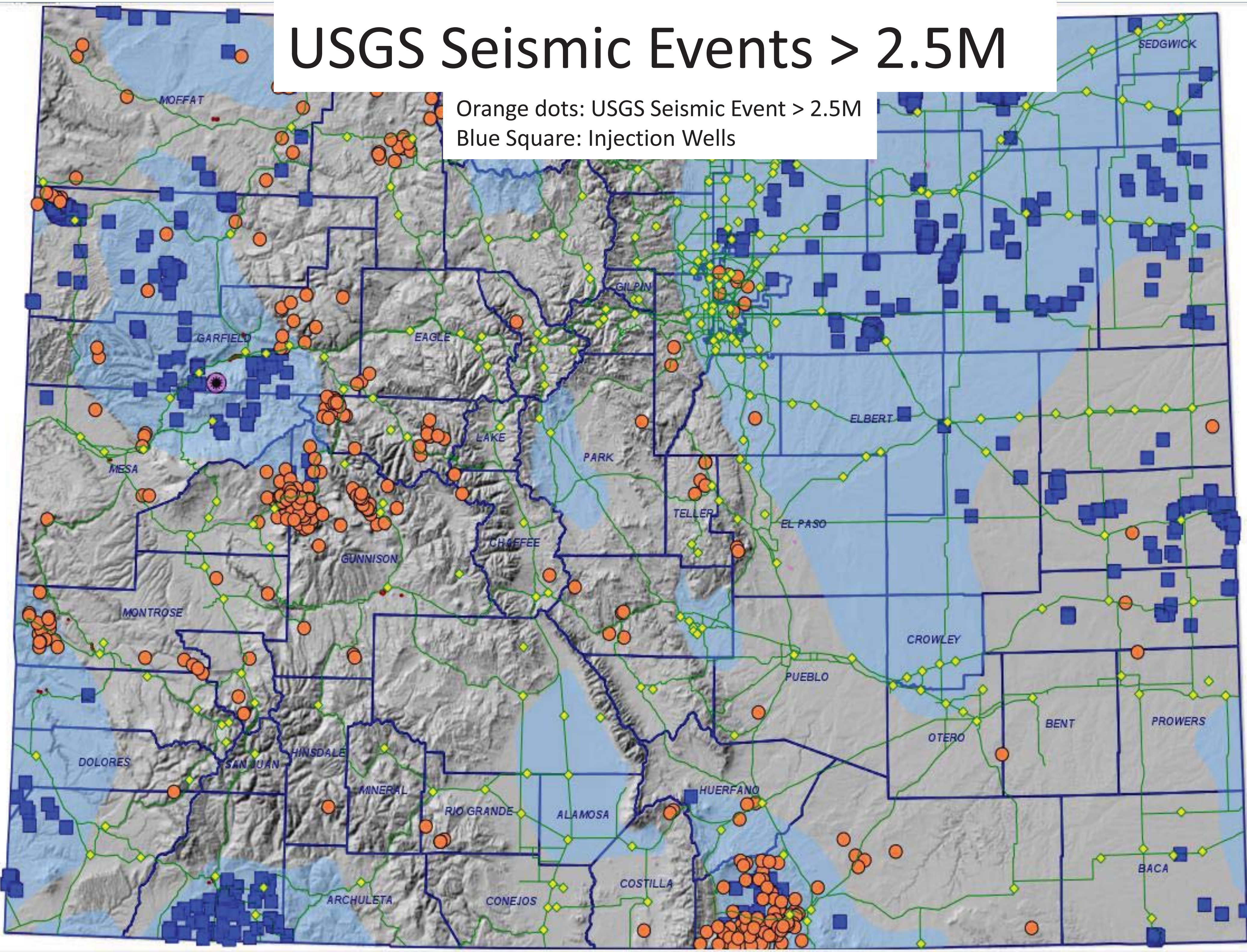
OIL & GAS CONSERVATION COMMISSION

COLORADO STATISTICS

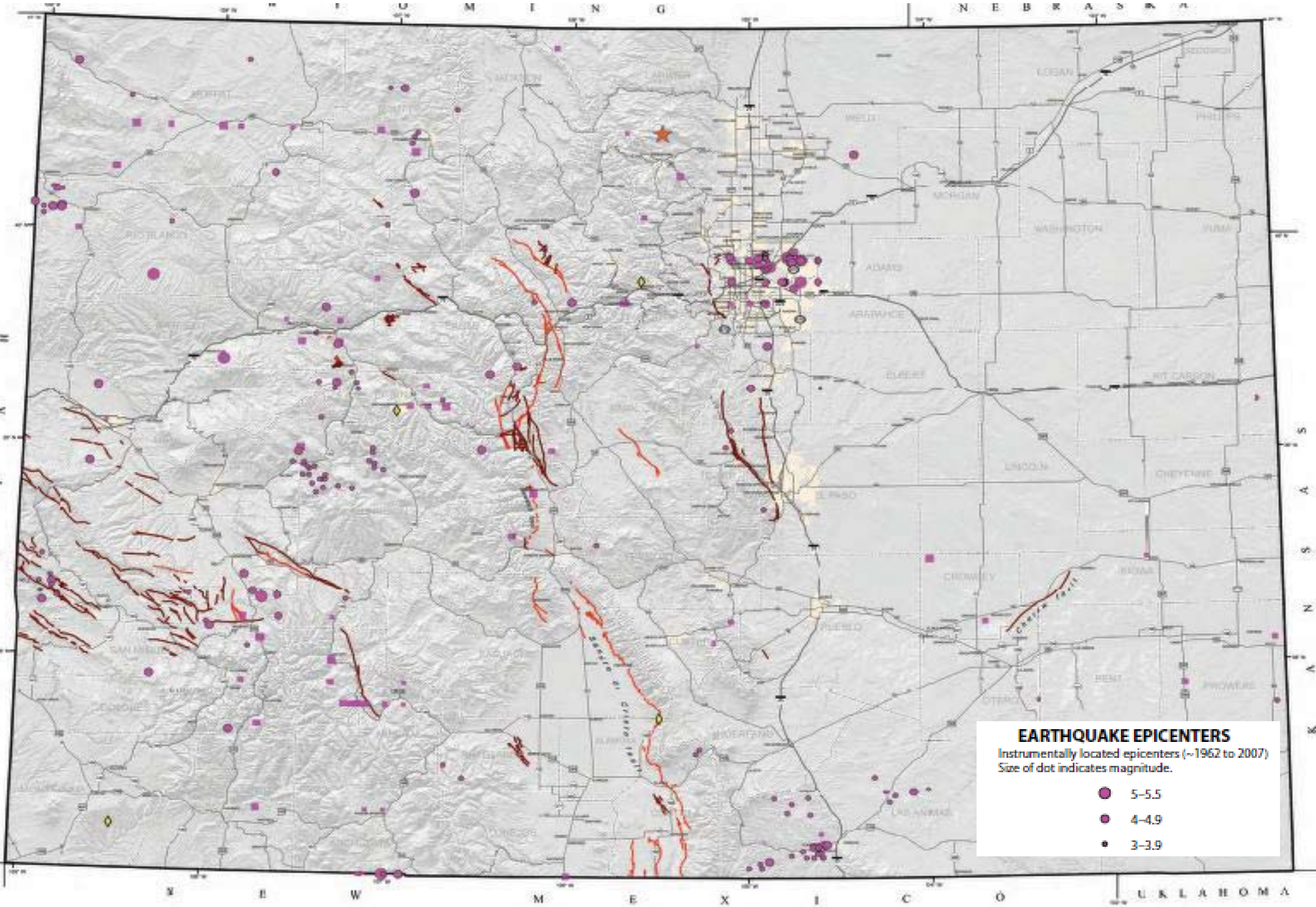
- As of January 1ST 2013,
  There are 920 Class II UIC wells
  - 350 DISPOSAL WELLS (34 are Tribal)
  - 570 ENHANCED RECOVERY WELLS (2 are EPS)

USGS Seismic Events > 2.5M

Orange dots: USGS Seismic Event > 2.5M
Blue Square: Injection Wells



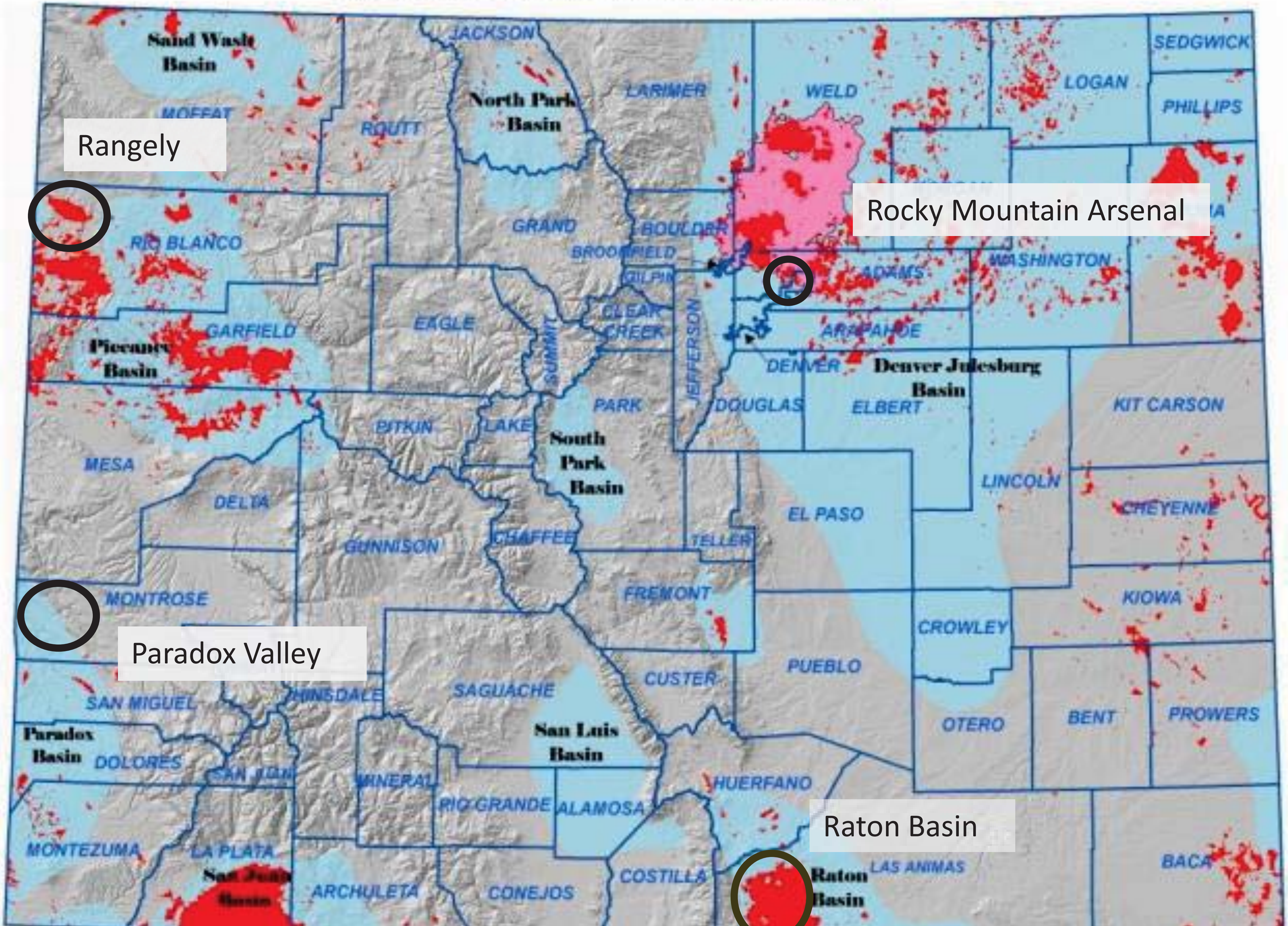
Colorado's Earthquake and Fault Map



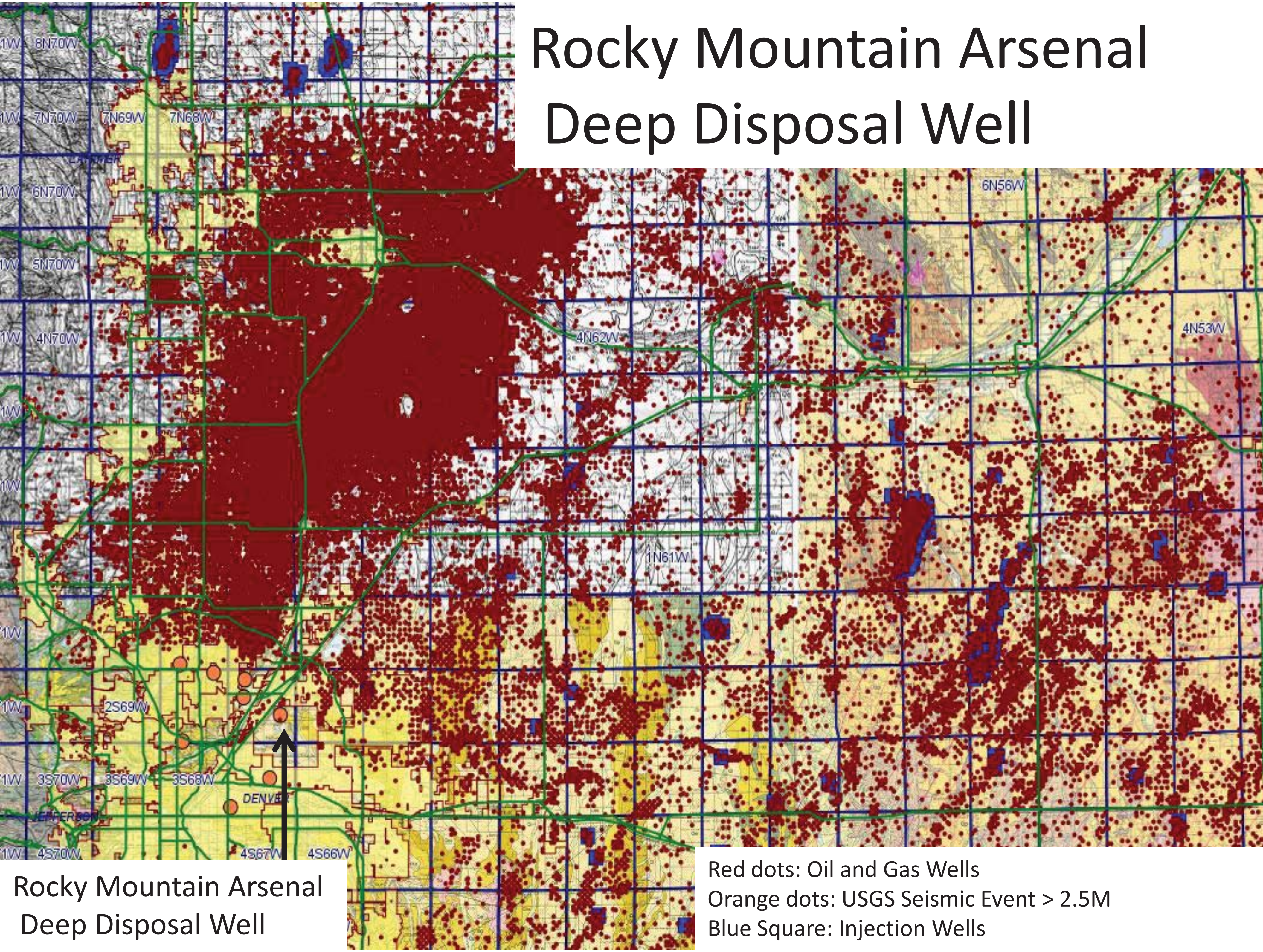
Three History Examples of Induced Seismicity in Colorado

- Rocky Mountain Arsenal, Adams County, CO *(1960s)*
- Rangely Oil Field, Rio Blanco County, CO *(1970s)*
- Paradox Valley, Dolores County, CO *(1990s)*

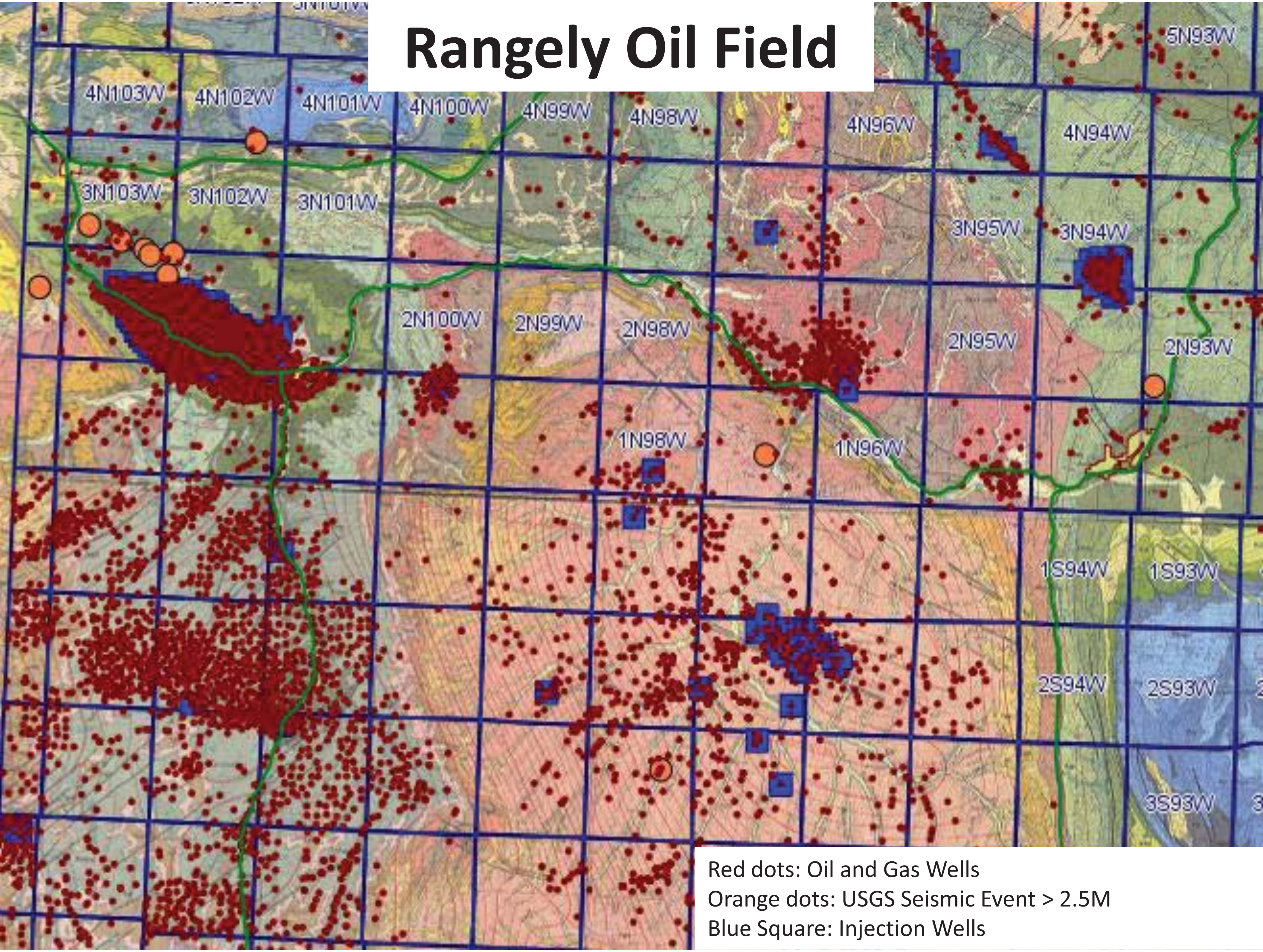
OIL AND GAS FIELDS IN COLORADO



Rocky Mountain Arsenal Deep Disposal Well

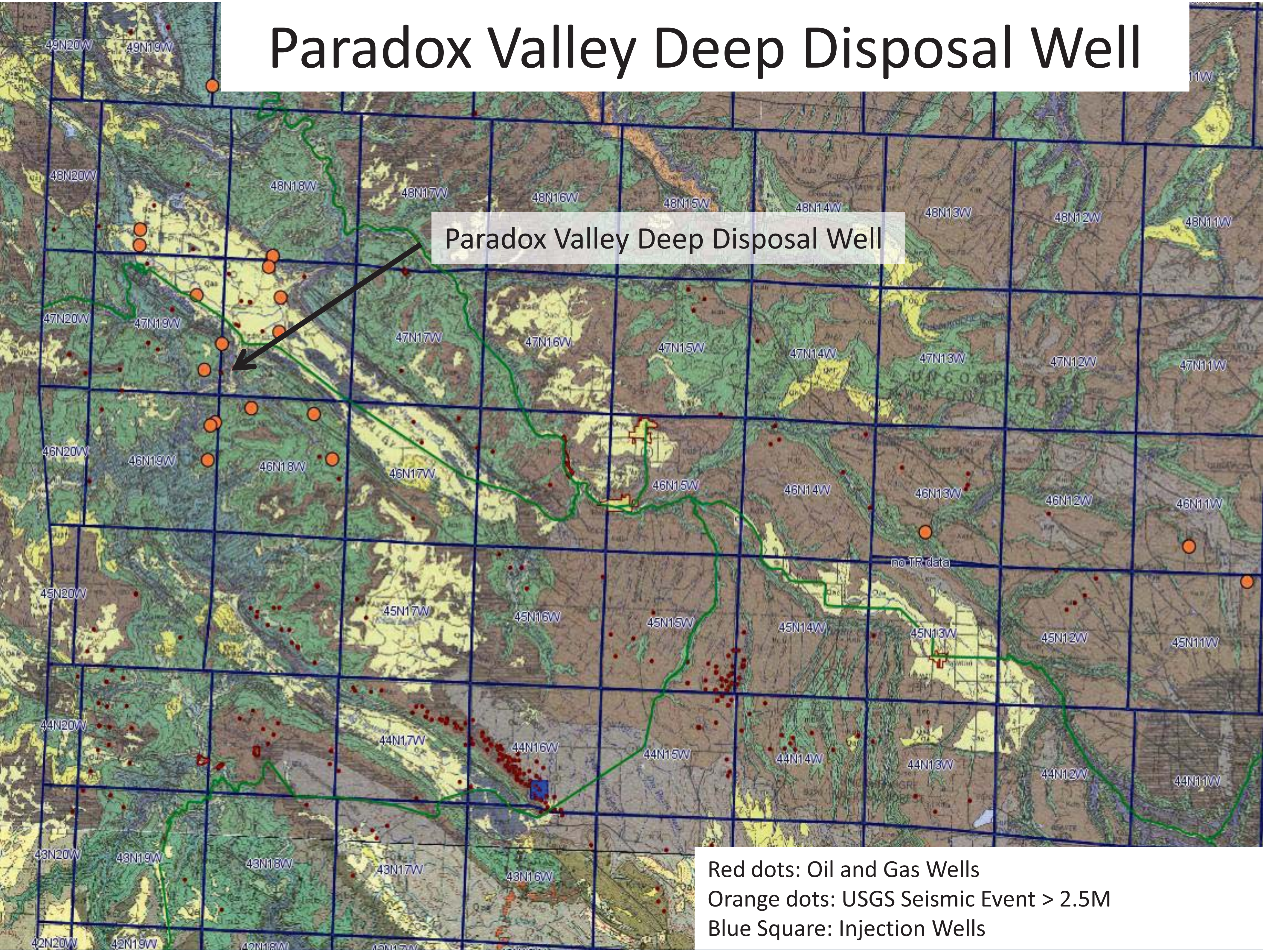


Rangely Oil Field



Red dots: Oil and Gas Wells
Orange dots: USGS Seismic Event > 2.5M
Blue Square: Injection Wells

Paradox Valley Deep Disposal Well



Red dots: Oil and Gas Wells
Orange dots: USGS Seismic Event > 2.5M
Blue Square: Injection Wells

Possible Causes of the Historic Induced Seismicity

- Rocky Mountain Arsenal,
  - Large injection volumes,
  - High injection rate
  - Low porosity reservoir
  - Low permeability reservoir

- Rangely Oil Field,
  - Large injection volumes,
  - High injection rate

- Paradox Valley, Dolores County, Colorado
  - Large injection volumes,
  - High injection rate
  - Low porosity reservoir
  - Low permeability reservoir

Safeguards

- Injection Volume Limits
- Injection Pressure Less than Fracture Gradient
- DWR Review for of Injection Zone
- CGS review for Seismicity

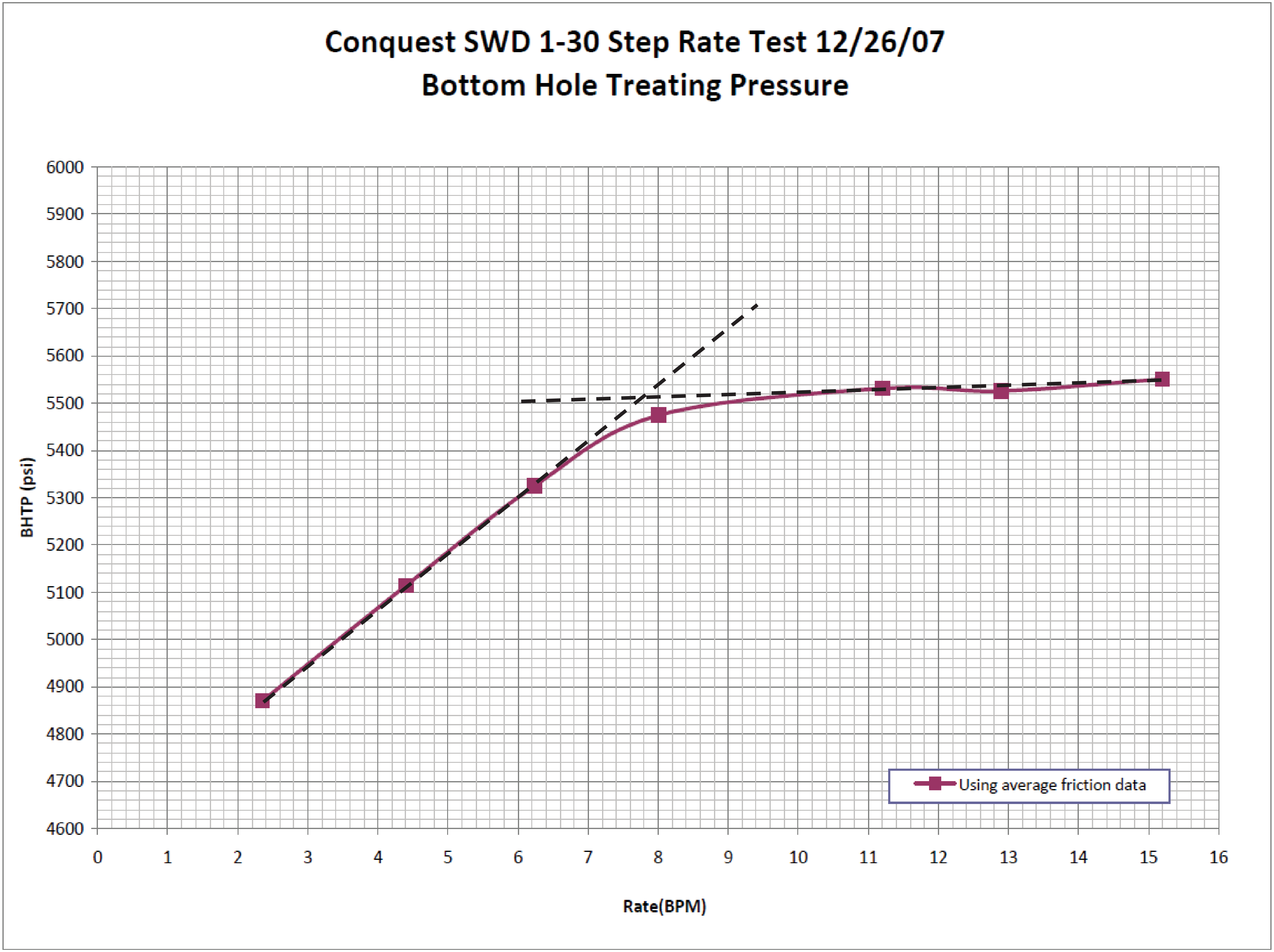
Calculation of Maximum Injection Volume

$$MIV = \phi\, h\, \pi\, (1/4 \text{ mile})^2$$

ϕ = Porosity

h = Reservoir height

π = PI


Conquest SWD 1-30 Step Rate Test 12/26/07
Bottom Hole Treating Pressure
BHTP (psi)
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Rate(BPM)
Using average friction data

Colorado Geology Survey Review

STATE OF COLORADO
OIL & GAS
OIL & GAS CONSERVA

WELL BORE DIAGRAM

PLACE & CEMENT PRODUCTION CASING

Fluid inflow prevented by cement

Per COGCC Rules 317.i, j, & k and verified per Rule 308A

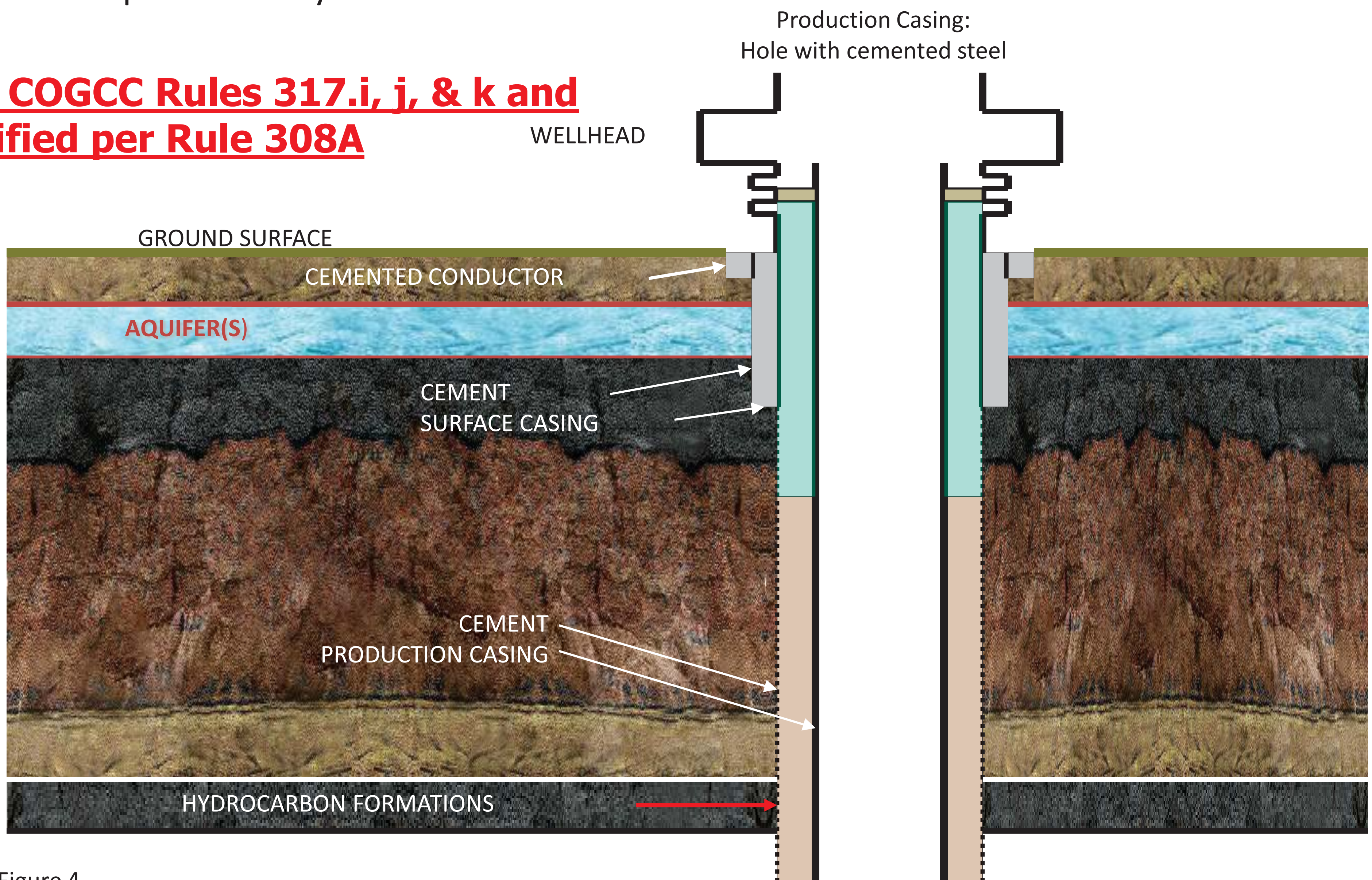


Figure 4

MECHANICAL INTEGRITY TEST

Applied pressure monitoring of internal casing pressure

Per COGCC Rule 326

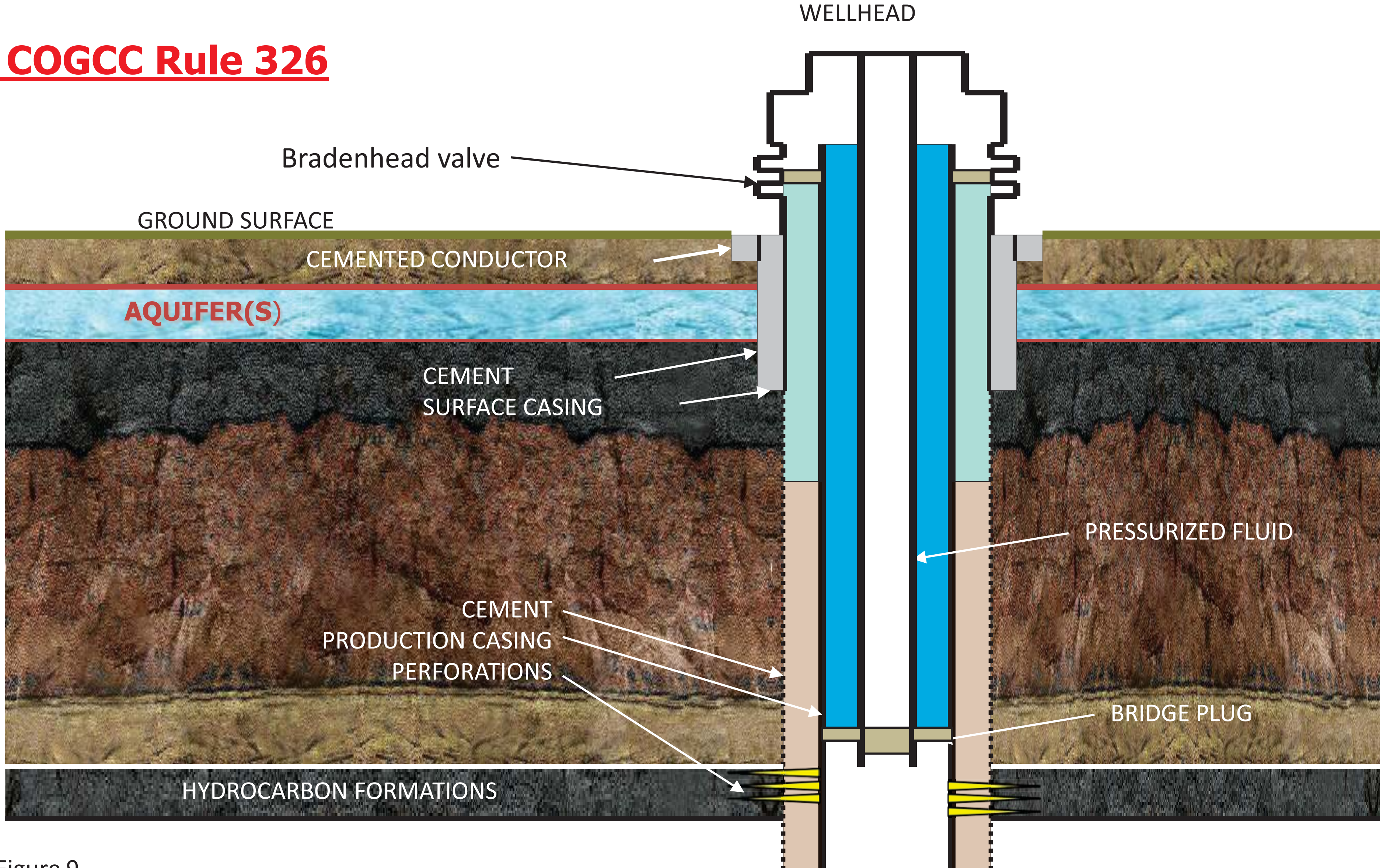


Figure 9

<u>STANDARD CONDITIONS OF APPROVAL</u>

- ALL APPROVED INJECTION PERMITS HAVE:

  ✓ MAXIMUM ALLOWABLE INJECTION PRESSURE.

  This pressure is set below the formation fracture pressure.

  ✓ MAXIMUM ALLOWABLE INJECTION VOLUME.

  - This volume is calculated to hold the *RADIUS OF INFLUENCE* of the injected fluid to ¼ mile.
  - This volume can be increased at a later date with additional approvals from COGCC.
  - This volume is not restriction does not apply to Enhanced Recovery Wells.

UIC ENFORCEMENT

FOR BOTH DISPOSAL AND SECONDARY RECOVERY

✓ ALL UIC WELLS INSPECTED YEARLY

- Injection pressure is checked
- Annular pressure is checked

✓ ALL UIC WELLS PRESSURE TESTED

- For casing integrity every 5 years.
- With a packer and tubing configuration;
- The tubing casing annulus is inspected for leaks; and
- Any well showing abnormal pressure in the tubing annulus is required to cease injection and be repaired of plugged.

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OGCC ANNOUNCEMENTS

HELP DESK SERVICE (12/06/2011) OIT HelpDesk Memo

WHO YA GONNA CALL? (12/05/2011) Help Desk Memo

LINK TO EFORM (INTERNAL HELP DESK) (12/15/2009) eForm

HOT TOPICS

Statewide Water Sampling and Monitoring Rulemaking (11/25/2012)
New and amended rules for statewide water sampling and monitoring. (600 Series)

Rulemaking to consider Statewide Setbacks. (11/25/2012)
New and amended rules for statewide setbacks and aesthetic and noise control. (100, 200, 300, 500, 600, 800, 900, 1100, and 1200 Series)

Setback Review Stakeholder Group (03/23/2012)
The COGCC Setback Review Stakeholder Group documentation web pages

Oil and Gas Industry Spills and Releases (10/13/2011)
This memorandum explains how the COGCC seeks to prevent spills and releases, and, when they occur, ensure that they are promptly contained, investigated, and remediated.

Hydraulic Fracturing Information (06/07/2011)
With the public's interest in and concern about the potential impacts of fracking on public health and the environment, the COGCC has compiled information for the public's review.

PUBLIC ANNOUNCEMENTS

Hearing Dates November through January Updated ! (11/08/2012)
Commission Hearing dates and times for November through January updated.

Current Job Opportunities At COGCC New
A listing of the current job openings.

December 10th and 11th Rulemaking Audio Available New
The December 10th and 11th Rulemaking Audio is now available for download. This is a large audio file and depending on your computer's ability, could take some time to download.

Industry Training Day for Form 5 and Form 5A (12/10/2012)
The COGCC Permitting and Engineering staff will provide Form 5 and Form 5A training for industry regulatory staff on Wednesday, January 9, 2013 at the COGCC Denver office.

November 14th Rulemaking Audio Available (11/20/2012)
The November 14th Rulemaking Audio is now available for download. This is a large audio file and depending on your computer's ability, could take some time to download.

November 15th Hearing Audio Available for Download (11/20/2012)
November 15th Hearing Audio Available for Download. This is a large audio file and depending on your computer's ability, could take some time to download.

New Form 10 Available in eForm (11/14/2012)
Form 10, Certification of Clearance and/or Change of Operator, is now available to be filed through eForm submission. A webcast recording and PowerPoint tutorial are available on the HELP page.

Jim Milne Named Environmental Manager (10/17/2012)
Jim Milne named Environmental Manager, effective November 1, 2012. Click here to see his Bio.

Form 41 Requirements and Instructions (04/24/2012)
Form 41, Trade Secret Claim of Entitlement instructions can be found on the Forms page.

Information on Hydraulic Fracturing Document (04/09/2012)
Click on the above link to download the COGCC document with Information on Hydraulic Fracturing.